TECHNICAL AND ECONOMIC ASSESSMENT OF MICRONIZED COAL PULVERIZERS AND A REVIEW OF THE CURRENT STATE OF MICRONIZED COAL COMBUSTION TECHNOLOGY

REPORT

BY

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MICRONIZED COAL STUDY

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1.0 EXECUTIVE SUMMARY

1. Micronized coal technology is an extension of conventional pulverized coal fuel firing technology requiring a finer degree of grinding or pulverizing.

   Pulverized coal is material of which 80% is smaller than 200 mesh (74 microns). Micronized coal is material of which 95% is smaller than 325 mesh (44 microns).

2. The greatest obstacle to its previous introduction has been that fine grinding is an energy intensive process that imposes severe burdens on pulverizing and grinding machines.

3. Improved designs and materials of construction are now enabling better machines for producing micronized coals to be manufactured, having capacities commensurate with the needs of industrial boilers, furnaces and kilns.

4. This report presents a technical and cost survey of the current status of micronized pulverizers for coals and reviews the current status of micronized coal combustion systems.

5. The report finds that the technology is reasonably well understood, it is based on empirical observations that do not allow precise prediction of system performance, either with regard to grinding systems or firing systems. This situation results from the extremely complex nature of coals. It requires a certain degree of practical testing in suitably designed pilot systems before the design data for full scale plant can be finalized.

6. Most of the development in micronized coal systems to date has been carried out in the USA or in other locations under USA licenses. A number of commercial industrial boiler plants are in operation but, although some electric utilities have carried out large scale trials, there are no utility electric generating plants using micronized coal firing at the present time.

7. One reason for a renewal of interest in micronized coal technology is that it has the potential for substituting for oil and natural gas in boilers designed to use those fuels. It therefore offers a means of increasing security of energy supply

and, until the oil price changes in 1986, also offered potential economic advantages. The current level of oil and gas prices has reduced this incentive and slowed the rate of application of micronized coal systems.

8. The technical and cost findings of this report are summarized in Tables 5.1 and 5.2. The tables show that a variety of mechanical systems using impact, compression and frictional forces are commercially available; and others are still under development to commercial scale.

9. Most systems appear to offer acceptable operating capabilities but long-term performances cannot be assessed yet. The principal components of the unit production costs of micronized fuel are energy consumption and fixed capital charges. The costs of maintenance do not appear to be of major significance. The substitution of oil or natural gas by micronized fuel can be made with minimal derating.

10. Additional progress in micronizing mills is expected to result from applications in other fields of minerals processing, some of which also have requirements for improved size reduction of solid materials.

11. Most of the manufacturers contacted in this work do not foresee difficulties in producing larger capacity units if the demand for them develops. Currently available units ranges up to 20 ton/hr.

12. The position regarding selection of small micronizing mills is more complex because mills of the fluid energy type become less efficient at smaller capacities than do mills employing rollers, hammers or other mechanical systems.

13. The variation of efficiency with capacity is also influenced by system recirculation loadings and whether systems can be operated in direct grinding or in semi-direct configurations, in which the product is held in intermediate storage before passing to the burners. Semi-direct systems are necessary where air/coal or steam/coal mixture ratios require adjustment before passing to the burners.

14. Further R&D is required to provide better understanding of optimum grinding systems for the different types of coal.

2.0 INTRODUCTION

This report presents the current status of development of micronized coal technology. The purpose of the technology is to improve the combustion characteristics of coals so that they may compete directly with, or substitute for, liquid or gaseous fuels in steam raising and process heating applications. Pulverized coal firing, in its present form, requires larger combustion equipment than oil or gas and cannot substitute for these fuels without substantial derating of capacity.

In performing the work Stone & Webster has contacted all known manufacturers of micronizing mills applicable to coals and having capacities consistent with industrial coal firing applications. The economic evaluations presented in Section 5 are based on the information obtained by this survey. Wherever possible, users of commercial micronizing mills have also been contacted to obtain information on mill performance and combustion data, which is reported in Sections 4.0 and 6.0. Reviews of the technical literature have also been made.

Almost all the development work reported is of U.S. origin; and where trials of micronized coal firing have been reported elsewhere, they have been based on American made equipment or manufactured under U.S. licenses. No developments, either of mill equipment or combustion trials, have been reported in Canada to date.

Micronized coal firing is applicable in conventional, dry form, as slurries of coal in oil or in water, or as coal/oil/water mixtures. The Terms of Reference of this study excludes forms other than dry micronized coal. Some of the equipment to be described has dry solid and liquid slurry applications but, for the reason stated, discussion is confined to performance with dry coal conditions.

The Terms of References also stipulated specifications for a small scale pulverizer capable of producing micronized coal at rates equivalent to 1 to 2 GJ/h (1 to 2 MBtu/h). The description of micronizing mills in Section 4.0 therefore includes references to minimum sizes and a basis for selection of a small unit in addition to the evaluations based on maximum capacities currently available.

3.0 COAL CHARACTERISTICS

The coal properties relevant to this discussion are (i) Grindability and (ii) Combustibility.

i) Grindability

Grindability is a derivative characteristic of coals that is dependent on a number of other empirical chemical and physical properties amongst which are microstructure and petrography; hardness; compressive strength; elastic properties; mineral matter content, moisture content and coal rank.

All coals are composed of petrographic constituents which exhibit quite wide variations in chemical and physical properties. Many investigations to separate and measure the properties of petrographic components have been reported. A typical investigation found the following Hardgrove Indices for petrographic fractions separated from a high volatile bituminous coal -

	HGI
Durain	16
Clarain	40
Vitrain	47
Fusain	120

indicating a range of grindabilities within a single coal as wide as is found in all types of coals, ranging from lignites to anthracites.

Coal Rank is a convenient method of classifying coals by type in the series passing from lignites, through bituminous varieties to anthracities. It cannot be defined by a single coal property and has no dimension but is inferred from the proximate analysis (dry, ash free volatile matter and fixed carbon values), caking and agglutinating properties and petrographic compositions. A general relationship of grindability (Hardgrove) and coal rank is shown in Figure 3.1 and 3.2, [10] which indicate that the easiest coals to grind are low to medium volatile bituminous types. Lignites and anthracites, at opposite ends of the rank scale, are harder to grind. The relationships are not precise enough to allow calculation of HGI from coal rank factors.

Grinding occurs by applying forces resulting in impact, compression or attrition of the coal particles, the particular types of mills used determining which of

these forces predominate. Thus roller mills principally apply compression and attrition whereas opposed jet mills rely more on impact and attrition. These are discussed more fully in Section 4. Whatever forces are involved, grinding requires significant energy inputs and the degree of size reduction achieved is a function of effective energy consumed. Attempts have been made to calculate the theoretical energy requirements of particle size reductions on the basis of certain mechanical laws. Hence Kick's Law asserts, in effect, that a material in a given state of size reduction represents a fixed quantity of work, whereas Rittinger's Law equates the energy input to the quantity of fresh surface of the particles produced. In practice attempts to apply these laws have not been successful. Energy requirements for crushing and grinding are also affected by the efficiency of the machines in transferring the energy to the particles and is a function of machine design. Practical measurements indicate the following energy consumptions:

Coarse crushing	3-4	kWh/ton
Fine grinding	20-30	kWh/ton
Superfine grinding	100-1000	kWh/ton

In general, less than 10% of the energy applied is used in size reduction, the remainder being dissipated as heat in the system. However, the energy required for fracture is only 0.1-1.0% of the theoretical energy required to create new surface for homogeneous solids, which difference is attributable to the heterogeneous microstructures of coals and their substantial microporosity. This is also confirmed by adsorption method measurements of unit surface areas which yield values much larger than the geometrical values calculated from particle diameters.

The variation of grindability with rank, in practice, means that the throughput capacities of grinding mills is lower for the harder coals, the balanced circulating loads in grinding systems at dynamic equilibrium being larger than for bituminous coals.

Other factors that have been found to affect grinding rates are feed size, moisture content, ash product size and mill condition. Values indicated in the Terms of Reference of this study are as follows:

Feed Size	< 7 mm (¼ in.)
Moisture Content	< 2%
Product size	100% < 44 microns

It is clear from this discussion that no single, specific parameter for predicting the grindability of any coal exists. It remains an empirical area in which, for a given coal in a given application, there is no substitute for direct testing and measurement. Reducing coals to micronized size specifications represents an extension of pulverizing methods that have been in large scale industrial use since the 1920's but this extension involves a degree of additional energy input and energy transfer to the grinding burden that cannot be achieved efficiently with any mills currently used in electric generating plants and large industrial steam plants. During the past decade, a number of grinding methods and machines have been under development, almost entirely by USA enterprises, to produce units having throughput capacities large enough and reliable enough to sustain large-scale firing of utility and industrial boilers. The current status of the progress is reported in Section 4.

ii) Combustion Characteristics

The combustion characteristics of coals are also highly coal-specific. The properties of greatest practical utility are the temperature of ignition, the rate of combustion and the total quantity of heat energy released. Coal is a solid hydrocarbon so that the heat released results from the chemical combination of the carbon and hydrogen present with oxygen in the air to form carbon dioxide and water as the ultimate gaseous products of combustion.

However, coal is also a highly microporous solid having an internal surface many times greater than the apparent external surface. The mass transport of oxygen to these surfaces and of combustion products away are diffusion processes that require finite times and are a function of coal particle size.

Also the solid coal hydrocarbon is thermally unstable and starts to pyrolize at temperatures well below those attained in combusting systems. The primary products of this pyrolysis are combustible gases, including tarry vapours and a solid char residue. The volatile gas/tar products burn faster than the solid carbon residue and their rate of combustion is mainly determined by their rate of production during pyrolysis.

The combustion of coal in any system, whether in fixed beds, fluidized solid beds or as pulverized suspensions is therefore primarily a matter of combustion of solid, porous carbon with sequentially prior or parallel

combustion of volatiles. The rate determining steps are the kinetics of pyrolysis, chemical reaction with oxygen and physical diffusion, the latter also being a function of particle size. These processes have been studied for more than 150 years but "overall, however, it can be said that such studies did more to define the problems than to solve then." [11]

During the past 25 years there have been substantial advances in understanding virtually all elements of the combustion mechanisms, resulting from greatly improved experimental design and by computer analysis and modelling techniques. In suspension fired systems 90-98% of the particles are smaller than 100 microns and it is now generally agreed that the combustion rate is largely determined by the true chemical kinetics for both pyrolysis (volatiles release) and char burnout, which is rapid, taking less than one second. See Table 3.1.

Heating rates and flame propagation speeds are also high. Diffusion kinetics are increasingly less significant as sizes fall lower than 100 microns and pyrolysis kinetics become less significant, relative to carbon burnout, as particle sizes pass into the micronized ranges below 44 microns.

In recent years, attempts have been made to reduce the complexities of the kinetics of combustion to mathematical models using computers, for single particle and multi-particle conditions. Models based on small laminar or flat flames with no backmix had been examined earlier but, by the early sixties, had contributed little to the fundamental understanding of the processes involved. It was clear that the models would have to accommodate backmix conditions generated by swirled and unswirled jet flames. In these conditions, it was known that heat transfer and combustion aerodynamics played a larger role than combustion kinetics, although the effect of diffusion on fluid flow was also significant.

These questions have now been studied by the Electric Power Research Institute (EPRI) and others as a result of which both one-dimensional and two-dimensional fluid mechanical models to describe pulverized coal combustion and entrained-flow gasification have been generated.[12] The one-stage model was developed to describe the response of a coal particle to its thermal, chemical and physical environment including one-dimensional fluid mechanics and radiative heat submodels. This was subsequently used to provide a

foundation for use in multi-dimensional modelling which is intended to predict detailed, local properties of the turbulent combustion process. Such models may be further developed in the future to help to elucidate the mechanisms of NO_x formation and control; and to evaluate the effect of injections of sorbents in multi-burner combustion.

The increased rates of combustion that result from micronization raises, in more acute form, the explosivity of suspensions of micronized coal particles. This hazard has long been recognized as being inherent in pulverized coal systems. The risks are reduced in practice by close coupling of grinding systems with furnace burners; reducing the volume of 'dead space' in the system in order to limit the total quantity of potentially explosive atmosphere; and maintaining the concentration of coal dust in primary combustion air at or above, the upper limits of flammability.

These factors have been re-investigated since 1980 in West Germany, where new systems for distributing bulk quantities of dry, finely pulverized coals, from central fuel preparation plants, have been introduced [14, 15, 16]. In these networks dry pulverized coals, mostly lignites but also bituminous coals are delivered by road, rail or water to bulk storage at user plants where the fuel is metered, mixed with primary combustion air and fired to conventional pulverized coal firing systems. Increased hazards are encountered in the storage and transportation systems and these have been intensively investigated in connection with the promulgation and enforcement of safety standards. This work has included the investigation of the following properties of coals, ranging from brown coals (lignites) to lean coals (anthracites):

- Spontaneous combustion characteristics
- Ignition temperatures
- Upper and lower dust concentration limits of explosive atmospheres
- Maximum explosion pressures in closed systems
- Maximum rates of time - dependent pressure rise
- Limiting values of oxygen concentrations

The ranges of results obtained by standardized testing methods are summarized in Table 3.2 and refer to coals containing less than 8% moisture and 8% ash.

The upper explosive limits generally exceed 2000g/m^3, equivalent to 1.63 lbs. of coal per lb. primary combustion air. Coal burners in conventional pulverized coal systems are normally fired at 0.5 - 0.67 lbs. coal per lb. air. The lower explosive limits range from 0.012 - 0.05 lbs. coal per lb. air. During start-up and shutdown it is probable that these ranges of limits are traversed momentarily, a situation that requires appropriate design measures to limit the quantities of explosive atmosphere created and to provide containment of small explosions using secondary explosion protection.

TABLE 3.1

COMPARISON OF BASIC COMBUSTION MODES

SYSTEM	PARTICLE SIZE mm	HEATING RATE °C	FLAME PROPAGATION m/s	REACTION TIME VOLATILES s	REACTION TIME CHAR s	FLUID/ PARTICLE SYSTEM
FIXED GRATES/ SHAFT GASIFIERS	< 100	< 1	10^{-5} - 10^{-3}	10^{2}	10^{3}	Counterflow
BALLASTED, FLUID BED	< 10	10^{3} - 10^{4}	Not Applicable	10 - 50	100-500	Particle backmix; fluid plug flow
PULVERIZED COAL* FURNACE/BOILERS	< 0.1	10^{3} - 10^{6}	10^{-1} - 10^{3}	< 0.1	< 1	Entrained particles in parallel flow

* Similar conditions apply to combustion of P.F. coal particles in diesel engines, combustion turbines and explosions.

TABLE 3.2 COAL EXPLOSIVITY DATA

Explosion Limits

Coal Moisture <8%; Coal Ash <8%

Lower Explosive Limits

Medium particle sizes <63	60 g/m^3 approximately
Very fine dust. High volatile coals	30 g/m^3 approximately
Highly reactive coals (lignites)	15 g/m^3 approximately

Upper Limits

Ignition (Smouldering) Temperatures

	In piles	Dust
Lignite	240°C	430°C
Anthracite	380°C	710°C

Limiting Oxygen Concentrations

Lignite	11% V/V
Anthracite	18% V/V

Maximum Explosion Pressures

Lignites/Bituminous Coals 7.8 - 10 bar

Maximum Rates of Pressure Rise

Lignites	153 bar/s
Lean Coals (Low V.M.)	30 bar/s

Flame Speed >200 m/s

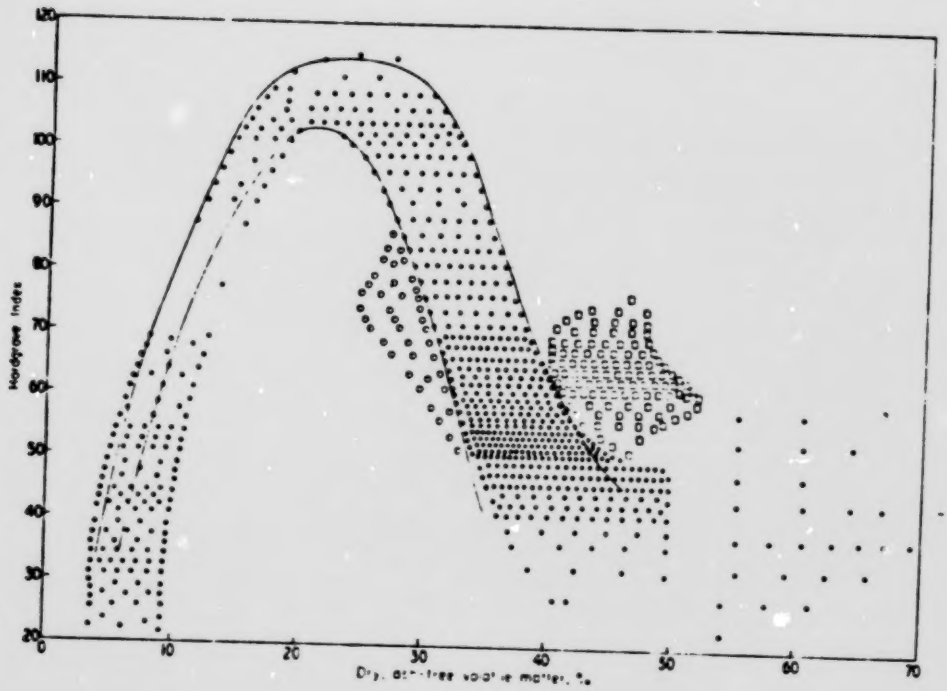


Figure 3.1 Grindability and Rank

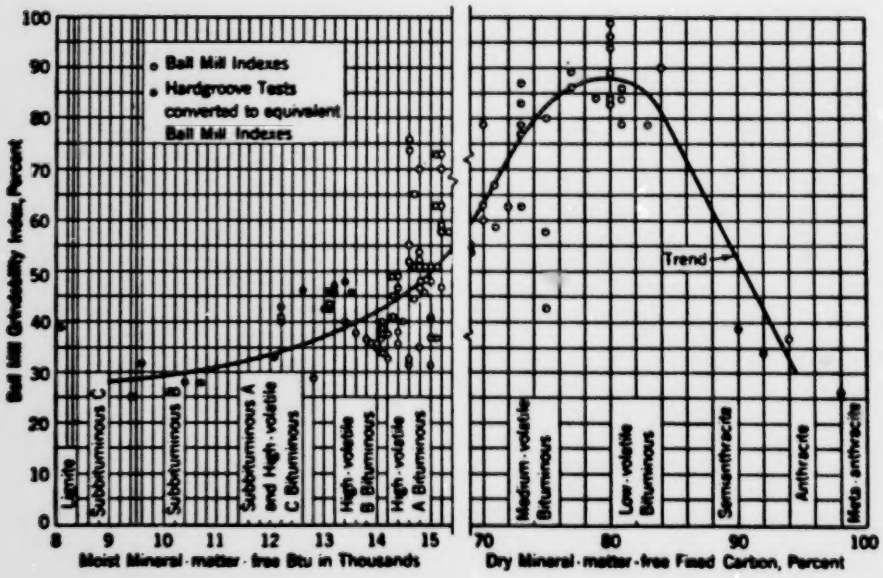


Figure 3.2 Relationship between Grindability and Rank

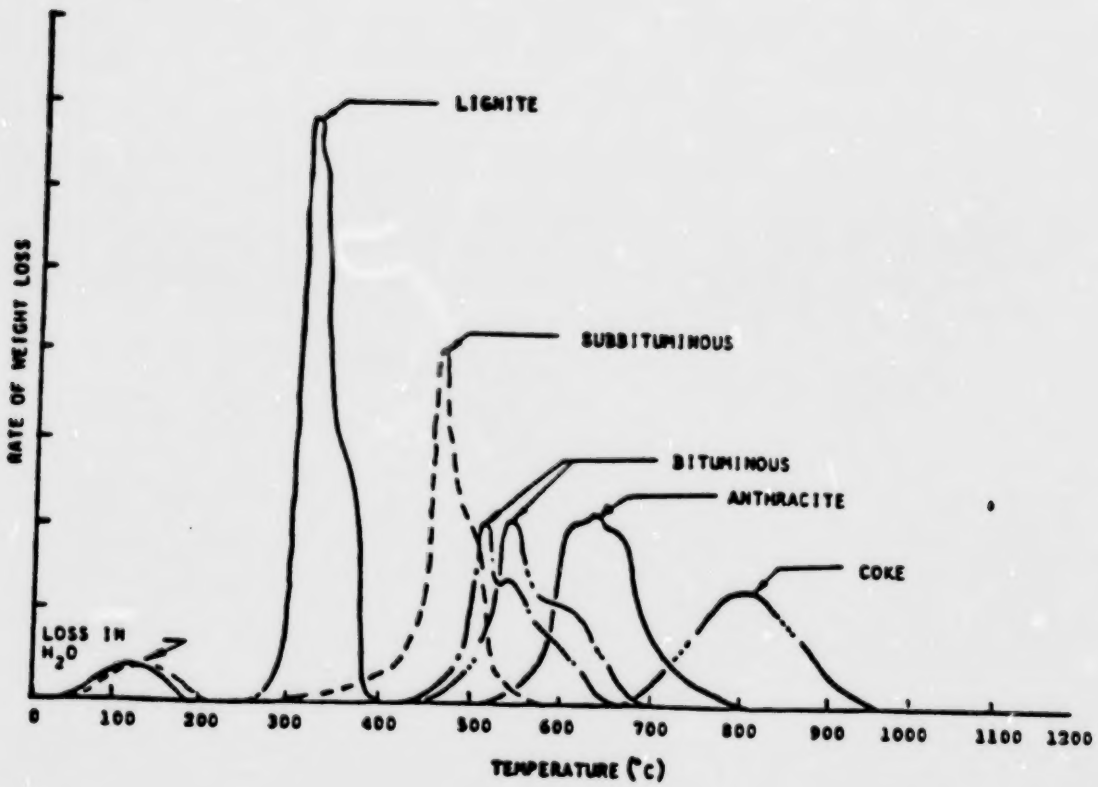


Figure 3.3 Combustion Profiles of Coals

4.0 TECHNICAL ASSESSMENT OF DRY MICRONIZED COAL PULVERIZERS

4.1 Classification of Pulverizer Systems

Section 4.0 presents a technical assessment of North American commercial pulverizers capable of producing a micronized coal grind. Seven pulverizer types have been identified and these can be broadly classified as either direct or semi-direct fired type as follows:

Direct Fired

- TAS Inc. Downflow Hammermill
- Ergon Inc. Fluid Energy Mill
- Kennedy Van Saun Ball Mill
- RMD Industries Opposed Jet Attrition Mill
- CP Coal Mills Inc. Centrifugal Pneumatic Mill

Semi-Direct Fired

- Bradley Roller Mill with Amvest Microsizer Classifier
- Williams Patent Crusher and Pulverizer Roller Mill

The above classification is somewhat superficial since pulverizer system hardware may vary depending upon the application. In some cases it may be necessary to modify a direct fired pulverizer system to a semi-direct type in order to meet specific coal, burner and boiler requirements.

Direct fired pulverizer systems are those in which air (or steam) fed to the pulverizer is used to dry the coal, fluidize it if applicable and transport the coal in dense phase directly to the burner. For a conventional burner, the primary air/coal ratio is generally in the range of 1.5-2.0 lbs. air per lb. coal. Variations in coal moisture content are usually accommodated by increasing or decreasing the primary air temperature to the mill, the air/coal ratio being unchanged. In applications where it is not possible to vary the primary air supply to the mill to such an extent that the air/coal ratio is too high for conventional combustors. In such cases, the pulverizer system may require modification to semi-direct fired type.

The semi-direct fired pulverizer system is one which incorporates an external cyclone for the purpose of disengaging the micronized coal from its transport medium, a separate primary air fan then being used to transport the coal from the cyclone bottom to the boiler in the correct air/coal ratio for a conventional burner.

The Ergon and RMD fluid energy mills can use either air or steam as transport medium. Both manufacturers consider their mills to be direct fired type even when using steam, though this may necessitate customized burners and/or supplementary fuel firing (oil or gas). Experience in this area for dry micronized coal firing is limited and must be considered on a case-by-case basis.

Typical schematics of direct and semi-direct fired pulverizer systems are shown in Figures 4.1.1 and 4.1.2.

4.2 Williams Roller Mill

Williams Patent Crusher and Pulverizer Co. of St. Louis, Missouri manufactures a range of mechanical roller mills for micronized coal with rated capacities in the range 1 to 8 ton/hr. The capacity of these mills is approximately 2-3 times the micronized coal rated capacity when producing standard pulverized coal grind (70% through 200 mesh).

The mill is usually direct fired type when producing standard pulverized coal grind using an air/solids ratio of about 2:1, but is classified in this study as semi-direct when producing micronized coal since the air/solids ratio may be 4:1 or higher which is unsuitable for conventional burners. With a cyclone in the system for disengagement of the micronized coal together with a product air fan giving an air/solids ratio of about 2:1, Williams claim a high turndown capability for the mill, limited only by the minimum conveying velocity. The semi-direct configuration of the mill as shown in Figure 4.1.2 was the one adopted by Idaho Supreme Potatoes Inc. for conversion of oil/gas to micronized coal at its Firth, Idaho plant in 1983.

An outline of the mill is shown in Figure 4.2.1. Operation of the mill system is completely automatic. The feeder introduces raw material of feed size up to 2" x 0 into the grinding chamber in the base of the

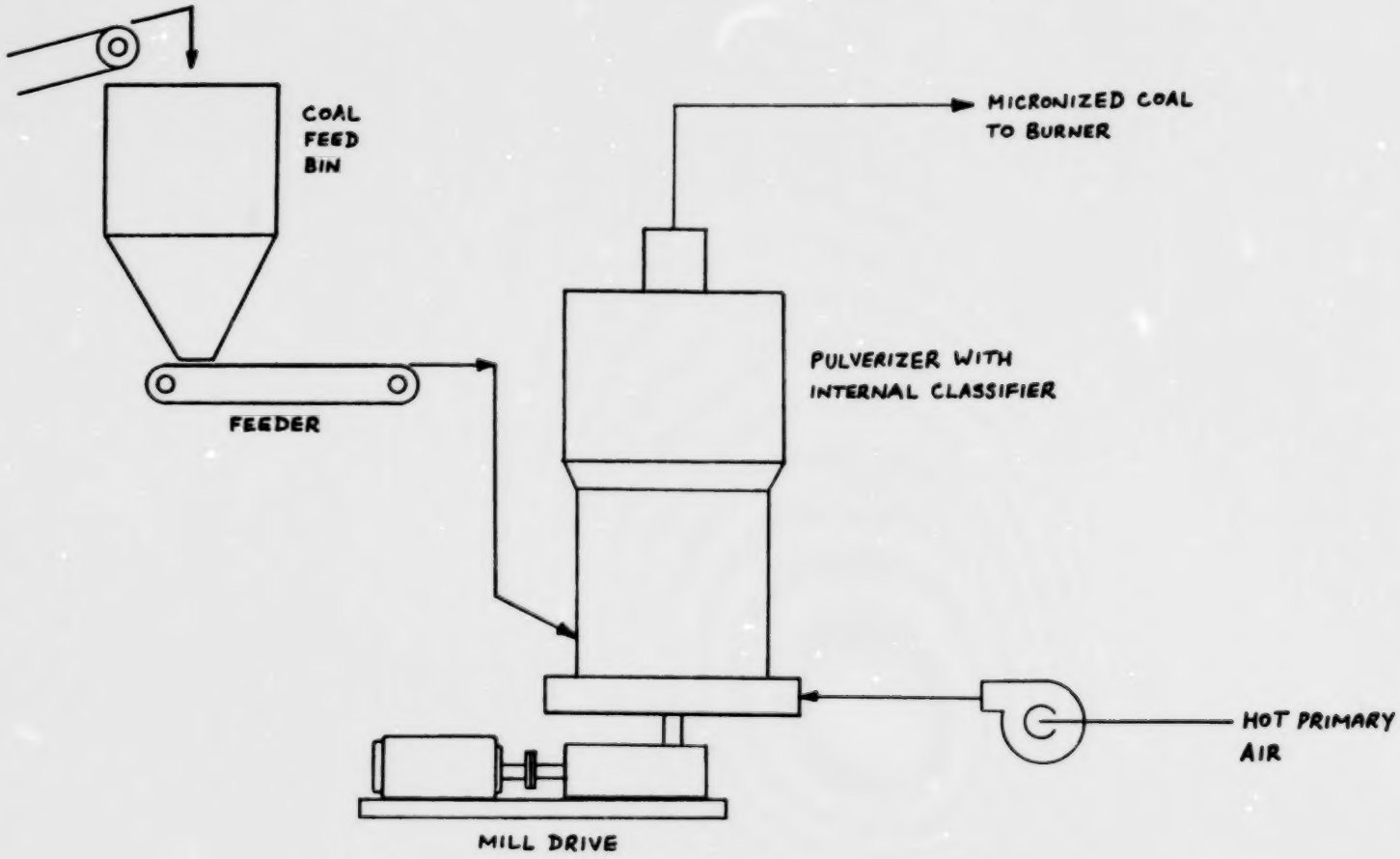


Figure 4.1.1 Typical Direct Fired Pulverizer System

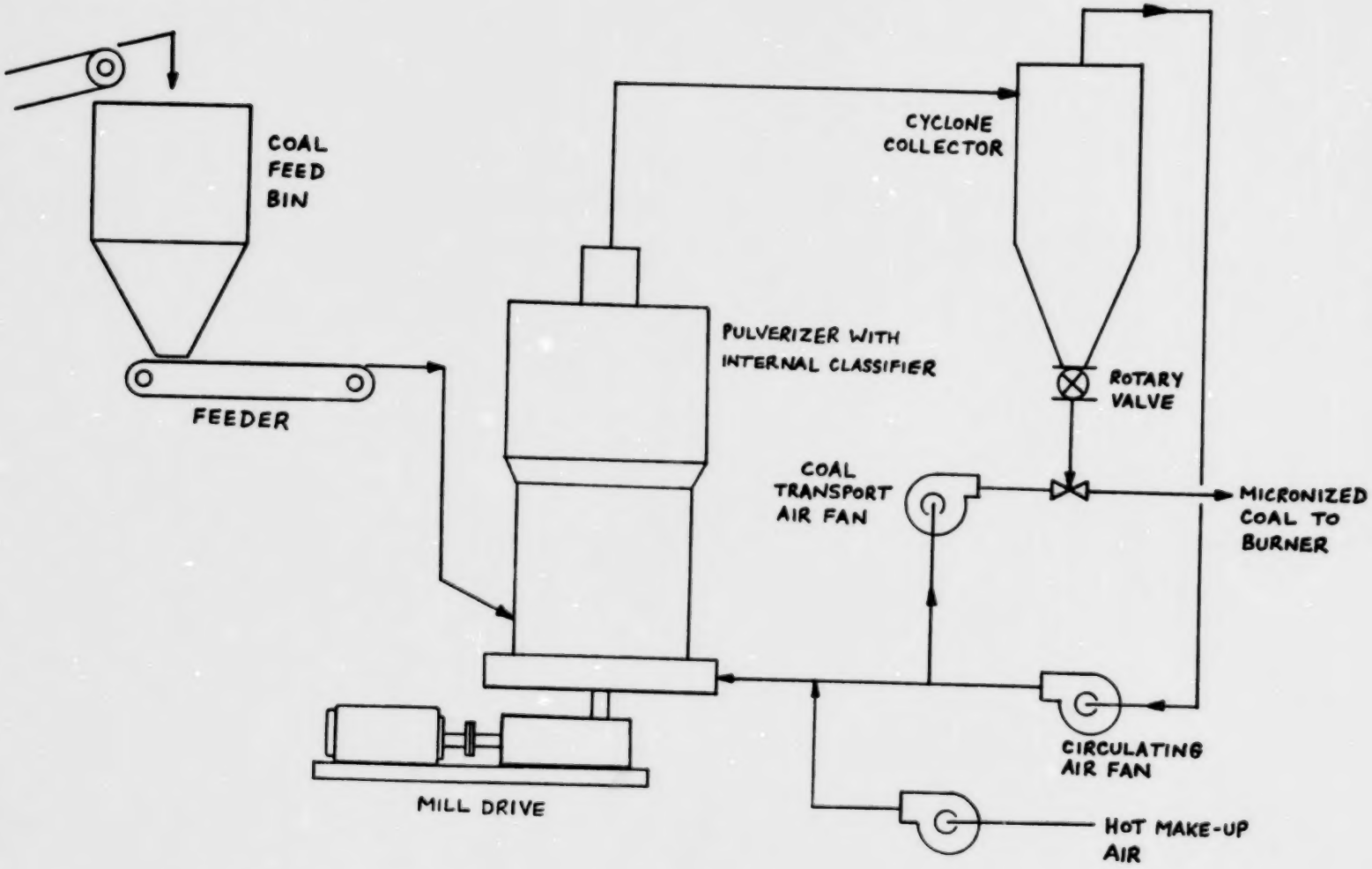
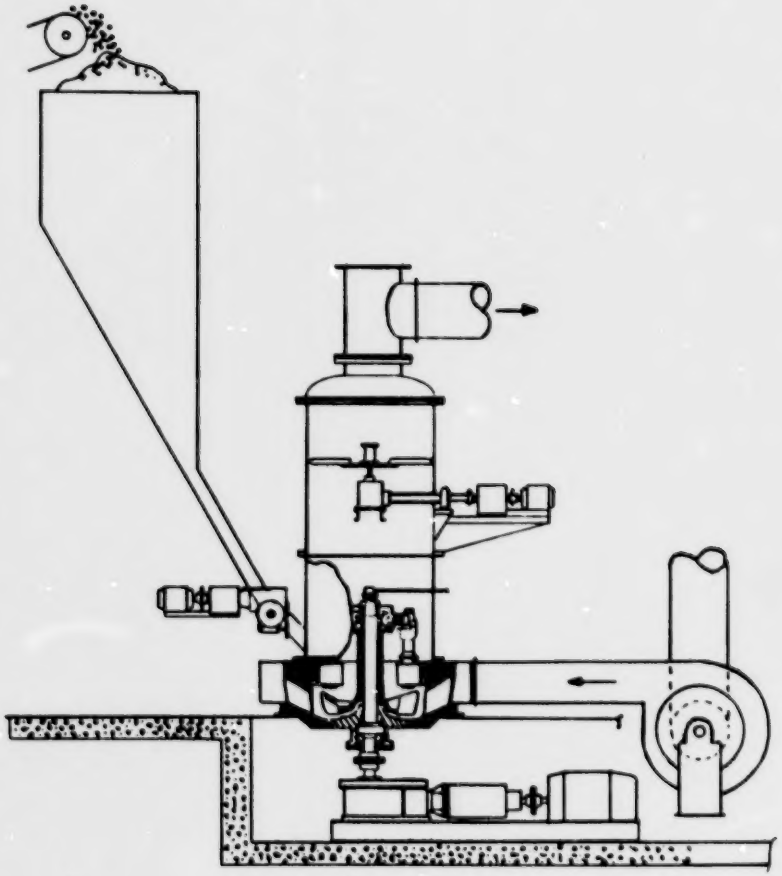


Figure 4.1.2 Typical Semi-Direct Fired Pulverizer System



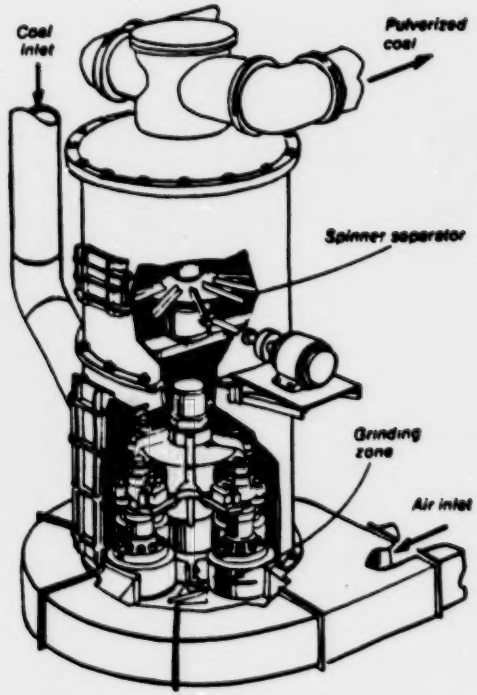


Figure 4.2.1 Williams Roller Mill

mill at a rate determined by pressure variations within the mill.

Plows located ahead of each roller direct the coal upward and between the grinding rolls and the heavy alloy steel bull ring where it is ground to size. The grinding rolls are free to swing out centrifugally which forces them to bear upon and grind the coal. Being free to pivot, the rolls automatically assume the proper position for grinding and need no adjustment to compensate for wear.

Ground coal is swept out of the mill by the controlled air flow from the mill air fan. Air suspended, the ground material passes through the adjustable spinner separator where an accurate size classification is made, oversize material being returned for additional grinding. Product size control is maintained by varying the speed of the spinner separator. Pyrites, tramp metal and slag producing impurities are removed intermittently or continuously via a discharge in the base of the mill. Drying of wet coals is simultaneous with grinding when hot air is introduced into the mill system.

Williams has found that for micronized coal, wear rates are about three times greater than for pulverized coal. Experience with two DF 74 (8 ton/hr. each) for COMCO, a subsidiary of Florida Power & Light, showed that replacement of the rollers and bull ring is generally required once per year. Williams estimates that the maintenance cost for predictable wear parts is approximately 20 cents U.S. per ton of coal pulverized.

Physical dimensions of the pulverizer including drive assembly range from approximately 2 m diameter by 4.3 m high for the small mill to 4.1 m diameter by 6.9 m for the largest mill.

Two important features of the Williams mill are the high turndown capability even with small size units, and the virtual linear relationship between unit size and power consumption of the pulverizer system. The average power consumption is 51.6 kWh/ton of micronized coal.

NORCO refinery in New Orleans was contacted to obtain user experience. The refinery has three DF 64 pulverizers, direct fired type, producing 90% through 325 mesh petroleum coke used to fire a Combustion Engineering boiler. While the mills have not been used since early 1987, NORCO confirmed that the mills met

the design performance and operated well. Of particular note was the good flexibility, responsiveness, turndown capability and controllability experienced with these units. NORCO stated that they had experienced no safety problems.

From telephone discussions with Williams on safety aspects of the mill system, Williams stated they had experienced no fires or explosions with micronized coal. For the semi-direct configuration, the cyclone rotary valve ensures that the cyclone operates empty to minimize risk of explosion. Operation of the mill during normal and trip conditions is handled automatically by the mill control system which is tailored to each installation and application.

Williams maintains a complete testing facility to undertake pilot runs on customer's coal samples including a 4 million Btu coal burner.

4.3 TAS Downflow Hammermill

The TAS pulverizer manufactured by TAS Corporation of Magna, Utah, is a vertical shaft downflow four stage impact and attrition type mill. The mill consists of a series of plate disk-mounted fixed cast steel hammers revolving at 2000-2500 rpm in an enclosed chamber lined with 1-inch thick wear-resistant blocks, generally as shown in Figure 4.3.1.

Grinding results from a combination of hammer impact on the larger particles and attrition of the smaller particles upon each other and across the grinding surfaces. An internal shaft-mounted fan at the bottom induces a flow through the mill. A damper at the air inlet meters the proper amount of air into the mill to sustain the turbulence required for continuous particle reduction. The mill does not employ an external classifier as TAS believe that one would not provide any benefit. TAS received a patent on the mill in 1985.

Present designs range from 0.6 ton/hr to 10 ton/hr. The small unit can turn down to 0.25 ton/hr. and TAS have made shop drawings for a 13 ton/hr. mill but which has not yet been fabricated and tested. For small and large capacity mills, the coal feed size can be up to 2" x 0 and the air/coal ratio is typically 1:1 or less. Coal throughput is varied by altering the rotational speed of the coal screw feeder and pulverizer and adjusting the air inlet damper position to maintain the

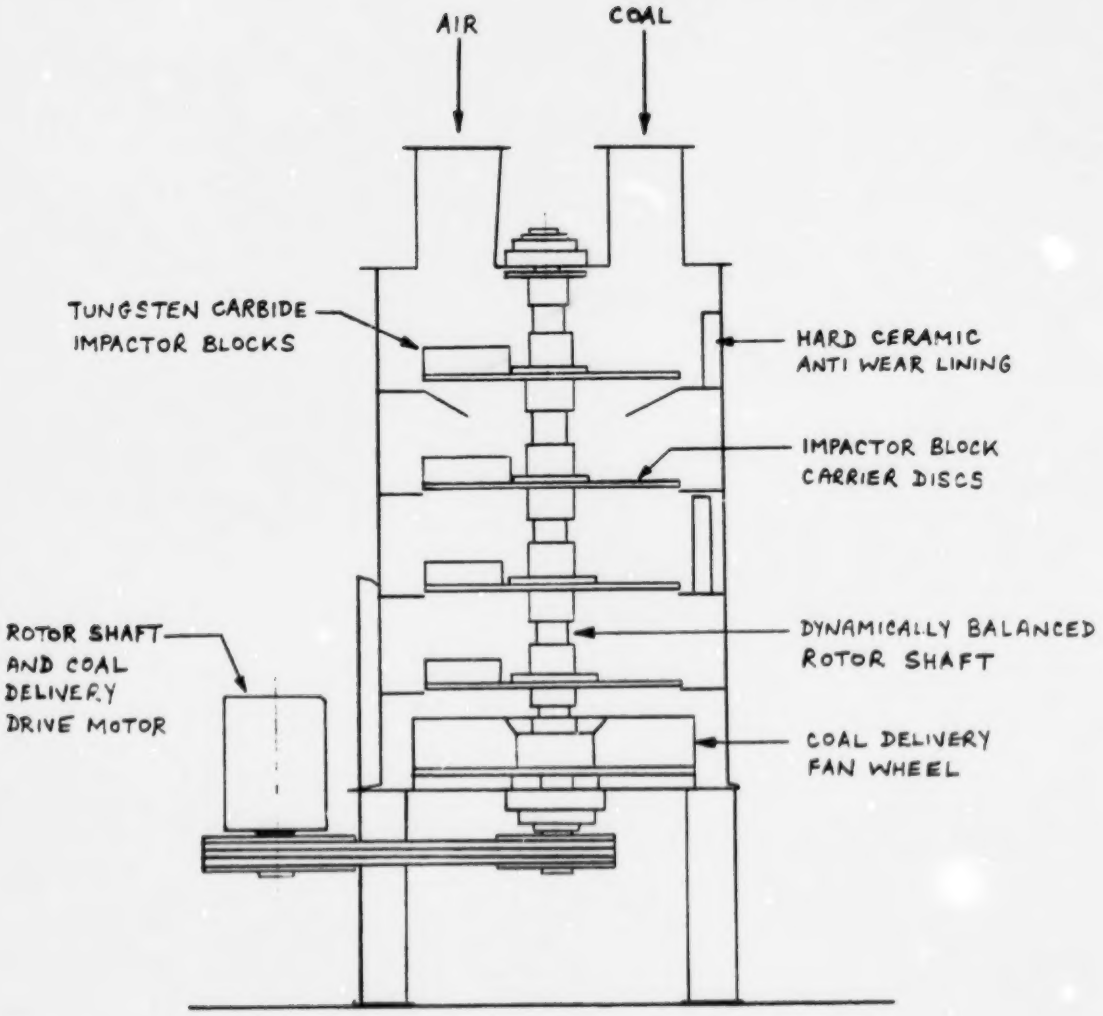


Figure 4.3.1 TAS Downflow Hammermill

correct air/solids ratio. Coal drying is achieved by varying the primary air temperature as in conventional direct fired mechanical pulverizers. However, coal moisture content has little effect on mill performance.

During 1983, Stone & Webster visited TAS and several users of the mill. The maximum capacity of the mill at that time was 5 ton/hr. One of the users was Kaiser Aluminum & Chemical Corporation which had a mill and burner installed on a rotary kiln used to dry potash at their Wendover, Utah facility. Shortly after start-up Kaiser performed some testing. Initial results at an energy consumption of 53 hp/ton/hr. were:

- 10% greater than 100 mesh
- 21.75% between 100 and 200 mesh
- 12.32% between 200 and 270 mesh
- 46% minus 325 mesh

Improvements were made producing the following results:

- 10.5% greater than 100 mesh
- 18.8% between 100 and 200 mesh
- 10.4% between 200 and 270 mesh
- 9.5% between 270 and 325 mesh
- 50% minus 325 mesh

Design modifications, including reducing clearances, improved performance to:

- 73% minus 325 mesh
- 50% minus 400 mesh

The energy consumption associated with these improved results was 86 hp/ton/hr.

Another 1983 visit was to a U.S. Gypsum plant in Sigurd, Utah, which uses two TAS pulverizers on two kilns. U.S. Gypsum was pleased with the TAS system. They advised that the rotors last from two to six months, with an average life of four months. It takes two men four hours to replace a rotor. Rebuilding the rotor costs $1800 U.S.

The third user visited in 1983 was L.D.S. Church in Salt Lake City which was using TAS system to fire a boiler. The boiler Superintendent was pleased with performance.

In 1983, Stone & Webster requested some samples from TAS and had particle size distribution performed at

Eastern Analytical Laboratories in Massachusetts. The samples and results are as follows:

- Sample 1 from TAS mill at Deutsche Babcock in Germany; South African coal with a 70 Hardgrove Grindability Index (HGI); 90% minus 325 mesh.

- Sample 2 from TAS mill at TAS; Utah coal with a 120 HGI; 99% minus 325 mesh.

- Sample 3 from TAS mill at Kaiser facility in Louisiana, Petroleum coke with a 60-65 HGI; 61% minus 325 mesh.

In December, 1986, Stone & Webster contacted Mr. Chad White of TAS to obtain updated information on the mill. When asked if the mill could achieve 98% minus 325 mesh, Mr. White stated that mill performance depends on the coal. This is in agreement with the general performance of mechanical mills which are dependent on the grindability of the coal (i.e. its HGI) and its surface moisture content. Mr. White stated that at Ideal Basic Industries cement plant in Utah, the mill is grinding a Wyoming coal and only achieves 82% minus 325 mesh. However, at another TAS mill installation with a different coal the mill is achieving 99% minus 325 mesh. The maximum mill capacity was claimed to be 10 ton/hr. However, he pointed out that the largest installation of the TAS mill to date was at Ideal Basic Industries and that mill is rated at 7.5 ton/hr.

In January, 1987, Stone & Webster contacted several TAS users by telephone. The Kaiser facility at Wendover, Utah has not used the mill since November, 1985. A fired occurred in the coal handling system and the current low price for diesel fuel has not warranted fixing the coal handling system in order to return to coal. In the two years prior to the fire they encountered no surprises with the mill. However, they never measured energy consumption or size fineness since the initial tests in 1983.

A Dole Mushroom Plant in Fillmore, Utah using two TAS mills to fire two Kewaunee 10,000 lb./hr. boilers was included in the 1983 TAS users listing. The plant has since been bought by Mushroom King and the maintenance supervisor was not employed there when the TAS mills were purchased. He was reluctant to provide detailed answers to questions. He stated that mill maintenance is high and that they have completely redesigned the mills. Stone & Webster advised him of the original

expected maintenance level of replacing and rebuilding rotor every four months and asked if the "high maintenance" he was experiencing was higher. His experience is apparently in that range, although he would not or could not provide specifics. They have not done any performance monitoring.

Stone & Webster contacted Bryant Giles of Ideal Basic Industries. They have a TAS mill system which has been in operation since September, 1986. It is rated at 7.5 ton/hr., but they have only operated it at 7 ton/hr. Another TAS mill will be installed in February, 1987. They are pleased with the mill. The only major problem has been with the motor. They have not performed any inspection of mill clearances or wear to date. The operating and maintenance instructions provided by TAS recommend inspection every six months. They have measured the power consumption of the mill motor but not the fan (at a production capacity of 7 ton/hr.). The 350 hp motor is operated at 4160 volts and was drawings 33 Amps. This converts to 27.3 hp/ton/hr.

The fan motor horsepower would be expected to be less than the mill motor horsepower, but the total would very likely exceed the 33 hp/ton/hr. claimed by TAS.

Mr. Giles stated the fineness to be:

- 99.9% minus 50 mesh
- 40-50% minus 325 mesh

This is not as good as the 82% minus 325 mesh, which Mr. White claimed for the Ideal Basic installation.

TAS was contacted again as part of this study and Mr. White stated that for a coal of HGI 50, the mill would typically produce 80% minus 325 mesh at 24.6 kWh/ton and 98% minus 325 mesh at approximately 30 kWh/ton. The experience of Kaiser and Ideal Basic Industries, however, indicates that the energy requirement to produce 98% minus 325 mesh could be triple the requirement claimed by the vendor. Mr. White considers that a maintenance cost of U.S. $0.29/ton is a reasonable estimate. TAS are willing to guarantee the performance of the mill following tests of customer's coal in their Utah facilities.

The TAS mill has also been installed extensively in the U.K. since 1980 through Stordy Combustion Engineering of Wolverhampton. As reported in the literature (CME July/August 1986), the capability of the TAS mill to

micronize coal was quoted as 80% minus 40 microns, which tends to support Stone & Webster's findings in North America.

Particular care is required with this mill to avoid tramp metal in the coal feed. An errant piece of metal can damage the rotor or an accumulation of trash on the rotor can cause imbalance with heavy vibration. The pulverized system should therefore include a magnet assembly ahead of the mill.

4.4 CP Coal Mills Centrifugal Pneumatic Mill

CP Coal Mills Inc., of Coralville, Iowa, a subsidiary of National Dynamis Corporation, manufactures a centrifugal mill as shown diagrammatically in Figure 4.4.1. The mill consists of a fan with bonded carbide coated impellers mounted above a cyclone with an abrasive liner. Air and coal (2" x 0) enter into the bottom of the cyclone and travel upwards to the fan. The fan discharges to an external classifier which recycles oversize back to the inlet. CPCM claim the mill can produce particles in the 3-40 micron size range with an average size of 12 microns. The cone supposedly acts like a fluid energy mill and grinding occurs primarily by particle to particle attrition through collisions in the air stream. According to the literature provided by the company, the U.S. Department of Energy has reviewed the mill and found substantial savings over conventional mills and capability to produce both a smaller particle size and a narrower size distribution than conventional mills. CPCM literature also discusses the benefits of firing micronized coal in boilers and combustion chambers designed for oil and gas firing. The company offers a complete prewired, skid mounted system, called the Microfuel system consisting of the mill and classifier, a multifuel burner and microprocessor controls (by Barber-Colman) requiring only burner piping, power supply and raw feed input.

From discussion with Mr. Allen C. Wiley, the President of CP Coal Mills Inc., National Dynamics also owns Nebraska Boiler Company and the mills are manufactured in Lincoln, Nebraska. A full scale demonstration unit is available in Lincoln for viewing by potential customers. CP Coal Mills prime target is asphalt dryers and they have at least one customer which is Dukane Asphalt Company in Lemont, Illinois.

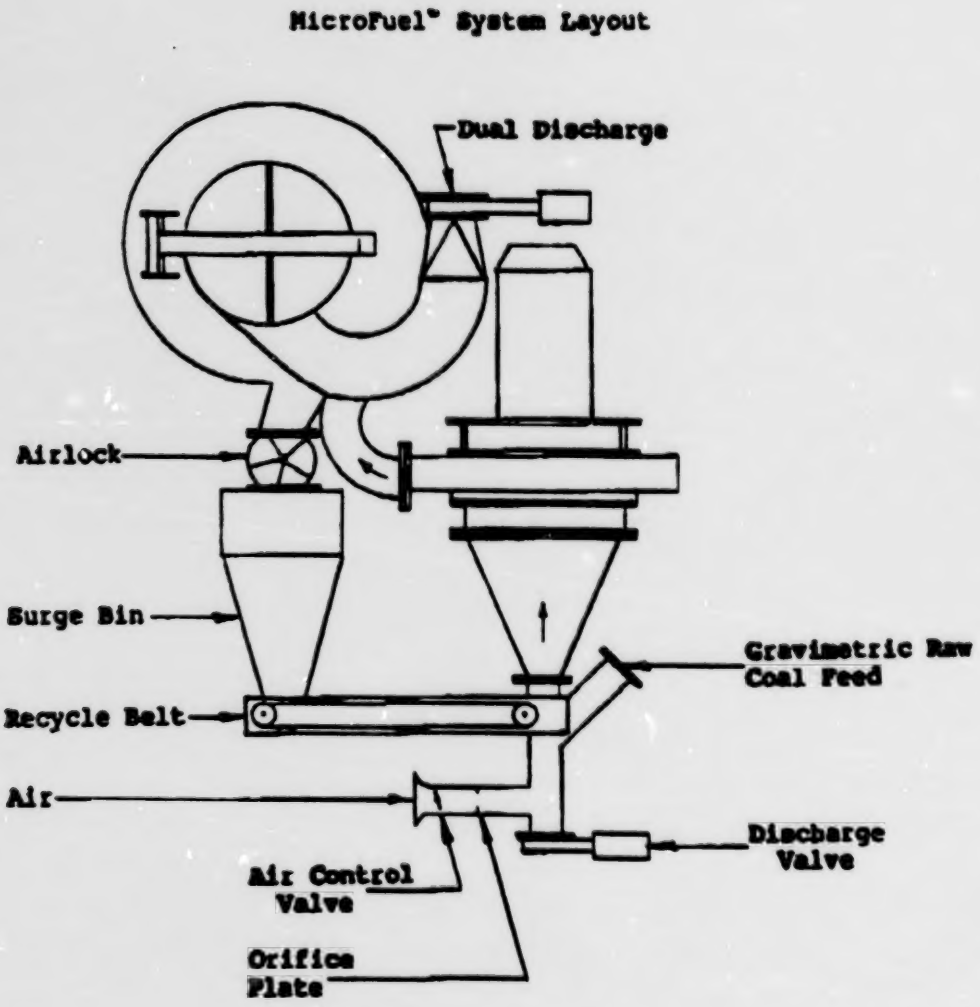


Figure 4.4.1 CP Coal Mills Centrifugal Pneumatic Mill

12/11/84
ALLEN C. WILEY / WILEY & ASSOCIATES
SAMPLE: B Midwestern Bituminious Coal
PROBE 30 SEC. @ 160 WATTS, TX-100, 100 SEC. RUNS

PARAM LABL	RUN # 1	RUN # 2	RUN # 3	MEAN AVE	STD DEV	COEF VAR
176	100	100	100	100	0	0
125	100	100	100	100	0	0
88	95.4	95.7	95	95.37	.35	0
62	89.9	91	89.7	90.2	.7	.01
44	82.1	83.4	83	82.83	.67	.01
31	67.1	68.9	68.1	68.03	.9	.01
22	53.4	53.8	52.7	53.3	.56	.01
16	40.5	40.9	40.8	40.73	.21	.01
11	30.1	31	30.5	30.53	.45	.01
7.8	21.5	21.3	21.4	21.4	.1	0
5.5	15.9	16	15.7	15.87	.15	.01
3.9	9.3	9.4	9.1	9.33	.21	.02
2.8	2.8	2.7	2.9	2.8	.1	.04
CS	.53	.54	.53	.53	.01	.01
MV	28	27.3	28	27.77	.4	.01
90%	62.5	59.5	63.2	61.73	1.97	.03
50%	20	19.9	20.3	20.07	.21	.01
10%	4.08	4.1	4.17	4.12	.05	.01
DV	.67	.68	.68	.68	0	.01
REC #	112	113	114			

DATA LOGGED ON DISC 17
C

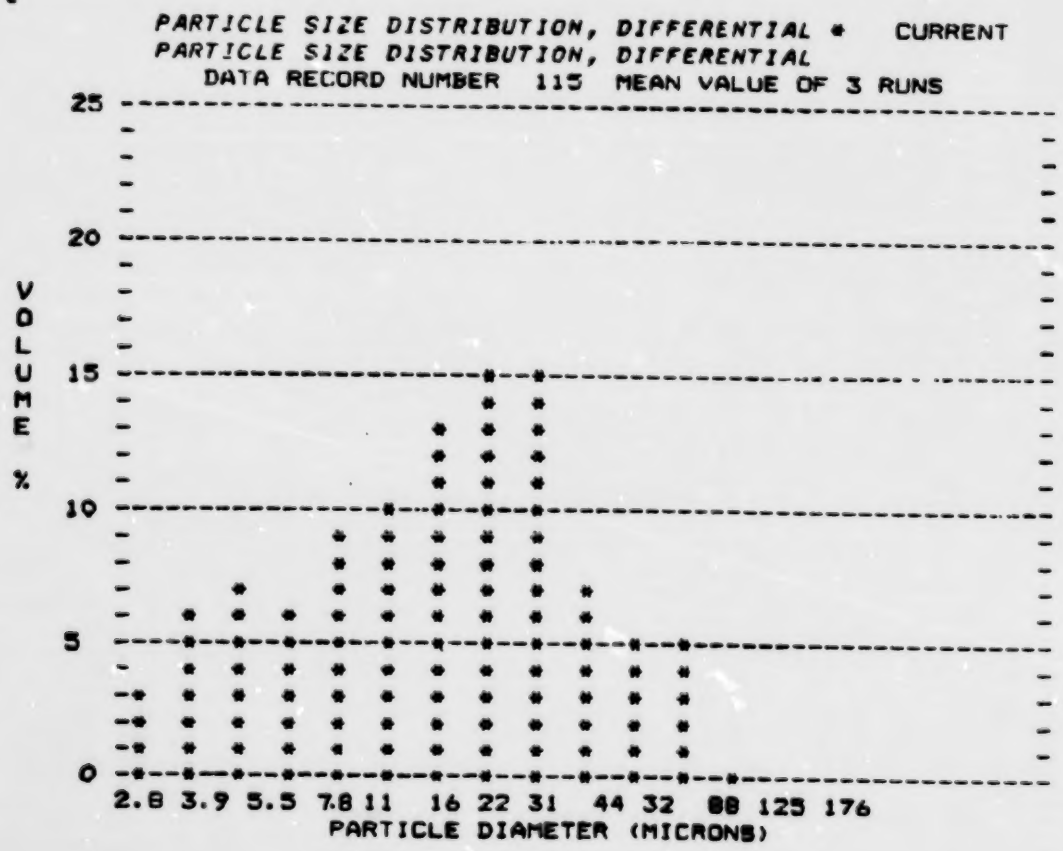


FIGURE 4.4.2 PARTICLE DIAMETER ANALYSIS FOR CENTRIFUGAL PNEUMATIC MILL

CPCM states that the mill does not require heated air, although if desired for combustion/boiler efficiency purposes, heated air can be used.

Three sizes are currently offered with rated capacities of 2.5, 5 and 10 ton/hr. By late 1988, CPCM expect to offer a mill in the 15-20 ton/hr. range. According to information from CPCM, micronized coal delivered to the burner is typically 92-95% minus 325 mesh, but 98% minus 325 mesh is achievable with classifier adjustment. Energy consumption is typically 24-28 kWh/ton for a variety of coals from sub-bituminous to anthracite. By contrast, energy requirements for producing standard pulverized grind coal are typically 13-17 kWh/ton.

Based on typical mill performance data submitted by CPCM, the recycle feed ratio is approximately 1.67:1 and the air/coal ratio from mill to burner is typically 1.6:1. Energy requirements depend upon the burner backpressure and are approximately 50% higher for a 12" W.G. backpressure compared to zero backpressure.

No information was obtained on turndown capability of the mill but, as for all mills employing fluid energy attrition, could be expected to be proportionately higher at lower loads. This is true also of smaller capacity mills which, according to CPCM, have higher energy requirements per ton than larger mill sizes.

The estimated maintenance requirements are:

- Recoat impeller with bonded tungsten carbide every 3,000 hours.
- Replace first section of the ceramic-lined scroll every 3000-5000 hours.
- Replace remaining ceramic sections every 6,000 hours.

4.5 Ergon Fluid Energy Mill

Ergon Inc. of Jackson, Mississippi manufactures a range of fluid energy mills which can use either air or steam as the transport medium. With either medium, Ergon intend that the mill is of the direct fired type. For micronized grind, the mill is known as the micro-pulverizer.

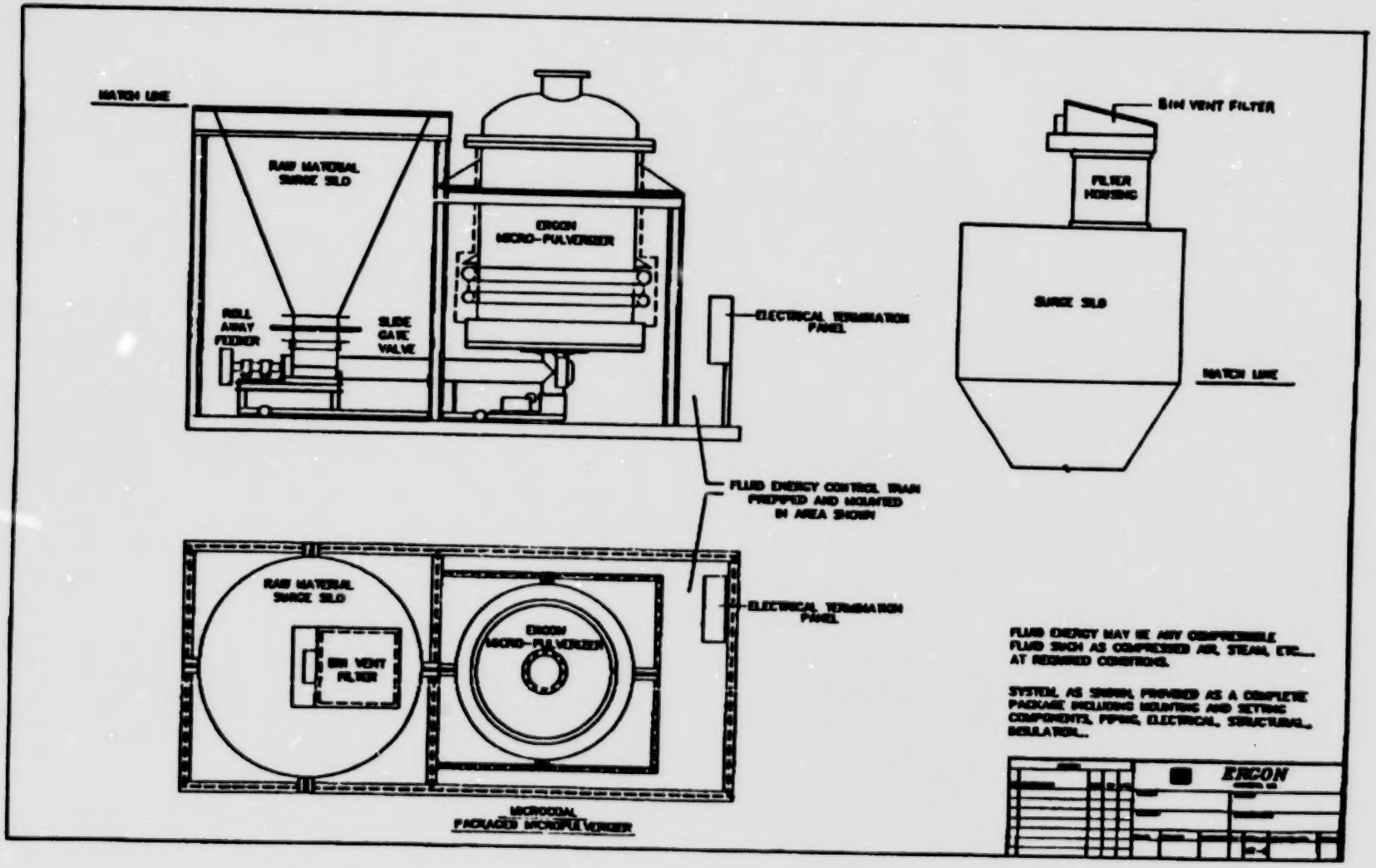

MATCH LINE
RAW MATERIAL SURGE SILO
ERGON MICRO-PULVERIZER
ROLL AIRAY FEEDER
SLIDE GATE VALVE
ELECTRICAL TERMINATION PANEL
FLUID ENERGY CONTROL TRAIN PREPIPED AND MOUNTED IN AREA SHOWN
BIN VENT FILTER
FILTER HOUSING
SURGE SILO
MATCH LINE
RAW MATERIAL SURGE SILO
BIN VENT FILTER
ERGON MICRO-PULVERIZER
ELECTRICAL TERMINATION PANEL
FLUID ENERGY MAY BE ANY COMPRESSIBLE FLUID SUCH AS COMPRESSED AIR, STEAM, ETC... AT REQUIRED CONDITIONS.
SYSTEM AS SHOWN, PROVIDED AS A COMPLETE PACKAGE INCLUDING MOUNTING AND SETTING COMPONENTS, PIPING, ELECTRICAL, STRUCTURAL, INSULATION...
ERGON

Figure 4.5.1 Ergon Fluid Energy Mill

Ergon offers a packaged system consisting of bin, coal feeder, mill controls, piping, support steel, electrical and instrumentation, generally as shown in Figure 4.5.1. The air compressor/steam source is usually provided by the owner.

Grinding of coal in the fluid energy mill is achieved by particle to particle impact and attrition in the fluidizing medium. The Ergon mill operates under a small positive pressure (less than 1 psig) but is totally dust free. Because the operation of the mill does not rely on contact between the coal particles and the mill surfaces to achieve particle size reduction, wear and maintenance are much reduced, as evidenced from tests and demonstrations to date. Correct alignment of the air or steam nozzles is critical to proper operation of the mill and avoidance of wear due to nozzle impingement on the shell. Because wear rates are reduced, the mill has the potential to produce a consistent product size over an extended period with high availability owing to the lack of moving parts.

Current maximum mill sizes are 25 ton/hr. for low rank coal on steam and 20 ton/hr. for air-ground bituminous coal of required physical properties. The minimum size for either grinding medium is 0.5 ton/hr. The preferred coal feed size is ¼" x 0 for air grind and ½" x 0 for steam grind, although 3/4" x 0 can be tolerated. Economics dictate that a mechanical mill, such as a hammermill, be used to reduce 2" x 0 raw feed to a maximum of 3/4" x 0.

Based on information received from Ergon, energy requirements (regardless of mill size) are as follows:

Coal Crusher - 1 to 5 hp per ton
Coal Feeder - 2 to 5 hp per ton
Classifier - none, stationary

Mill:

a) Air grind, electric compressor - 135 to 180 hp/ton

b) Air grind, steam turbine/compressor - 1.2 lb. sat. steam/lb. coal

c) Steam grind - site specific @ 0.8 lb. steam/lb. coal

The required fluid conditions are:

- Steam @ 150 psig/680°F minimum
- Air @ 40 to 90 psig/250°F based on 5-8% moisture coal

Ergon point out that the smaller the feed size, the more tolerant the mill is of coal moisture content. They have fed 12.5% moisture coal at ½" x 0 with no problem but did have to raise the air temperature to approximately 325°F.

Steam grinding offers the advantages of being inert and producing a slightly better product size. According to Ergon, steam will produce 98% 325 mesh, whereas air will generally produce 96-97.5% minus 325 mesh. Mean particle size tends to be larger for air; for example, if 6 micron for steam, then 8-10 micron for air. The main disadvantages with steam are the loss of energy in the boiler and the need for customized burners. Also, at plants where a ready source of steam with the required conditions is not available, steam grinding will not be economically viable.

The air or steam to coal ratio tends to increase in the smaller mill sizes particularly. Mills smaller than 1 ton/hr. require approximately 25% more fluid energy per ton of coal than the larger sizes.

Some turndown is possible on the Ergon mill but steam or air requirements do not reduce in proportion to coal throughput. For example, at rated output the mill may require 2 lb. air/lb. coal, but at reduced loads may require 3-4 lb./air coal. Since this may present problems in combustor design, the Ergon mill could have limited turndown capability in air grind applications involving micronized coal combustion in boilers. Mill parameters, energy requirements and control system must be tailored for each application.

Maintenance costs for the Ergon mill, excluding the fluid energy source, are approximately U.S. $ 0.17 per ton. As mentioned previously, wear rate of the mill surfaces should be very low with correct alignment of the nozzles. Fluid temperature must be maintained in order that condensate does not form in the nozzles and cause wire drawing.

Micronized coal operating experience is limited to testing by Ergon and James Howden and Company and demonstrations at boilers located at the Mississippi Power & Light Delta Station and at an industrial plant

in Wales, U.K. Howden is the license for the Ergon mill in Europe and other parts of the world.

Howden's microcoal firing trials on the Courtaulds test boiler in North Wales ran for 62 weeks June 1984 and August 1985. A single 5 ton/hr. steam grind mill was used to feed directly to a 90,000 lb./hr. two-drum industrial boiler designed for oil firing. The only modifications to the boiler which was designed for oil firing were replacement of the four heavy fuel oil burners with four dual-fired microcoal/heavy fuel oil burners, burner quarl modifications and additional sootblowers. Since no air preheat was used, continuous oil support of around 10% of the total heat input was maintained to avoid the possibility of a boiler flame-out. Different bituminous coals were tried of varying quality. For good feed coal, overall performance was very encouraging with combustion efficiencies of around 99% at excess air levels of around 15%. Power feed coals containing much higher fines and moisture contents led to more variable feed rates to the mill and higher unburnt carbon levels as a consequence. The availability of the mill throughout the trial period was 97-98% [17].

4.6 Bradley Roller Mill with Microsizer Classifier

In March, 1981, Progressive Industries of Sylacauga, Alabama received a patent for a centrifugal air classifying apparatus which they called a Microsizer. In January, 1985, Amvest Corporation acquired the assets of Progressive Industries. Amvest is working with Bradley Pulverizer Company to develop the microsizer classifier into what they call the RMC ultrafine grinding system. Originally developed for multi-stage classification in industries requiring ultra-fine materials ranging from 100% minus 3 microns to coarse product applications, the Microsizer is a cyclone and for micronized coal applications would be used to disengage the transport air carrying coal from the mill, as shown in Figure 4.1.2. The overall pulverizing system becomes very similar, therefore, to the Williams system in Section 4.2.

Raw coal is fed to the grinding mill by a vibratory feeder. The rate of feed is controlled automatically based on mill motor amperage. Air from the mill fan is introduced at the base of the mill and carried the ground coal upwards from the grinding section. An integral fineness selector (variable speed classifier) permits only the finished product sized particles to be

conveyed by the airstream to the cyclone collector. A product air fan conveys the coal to the boiler at the correct air/solids ratio for a conventional burner. The mill system operates under slight negative pressure to ensure dust-free operation.

Current designs range in size from Model BPH 3 with a rated capacity of 0.6 - 0.75 ton/hr. for the same grind. Bradley currently have a Model BPH 50 (22 ton/hr.) on the drawing boards which has yet to be built. The preferred maximum coal feed size is 1-3/4" x 0 for the large mill and ½" x 0 for the small mill, although 2" x 0 is acceptable for the large unit. Coal moisture content must be less than 1% in the feed or hot air must be supplied to dry the coal in the mill.

In 1985, Bradley developed a new vertical blade variable speed classifier known as the RMC classifier which doubled the capacity of the mill when producing a micronized grind. Prior to this development, the classifier was the limiting feature of the mill to produce a consistent product particle size.

From telephone discussions with Bradley, the air/solids ratio for the mill is approximately 7:1, considerably higher than the Williams mill which has a similar mechanical design. The explosion risk depends upon the coal type and required mill air temperature for coal drying. Bradley indicates that where the risk of an explosion is higher, an inert gas such as nitrogen can be used. They did adopt this approach when conducting coal grinding tests to 90% minus 325 mesh for the Texas Cement Co. involving a coal having 50% volatility and a hardness of HGI 28. The fact that the pulverizer system is semi-direct type with the transport medium operating in a closed cycle makes the use of nitrogen theoretically possible. However, the equipment would need to operate in a tight fashion in order to minimize costly nitrogen make-up requirements.

Bradley indicates that dual cyclones would be used for the larger mills, but a single cyclone only is required in the small size range. Typical space requirements for the BPH 30 mill system are 10 m x 15 m x 16 m high at the cyclones including the mill, mill air fan, cyclones and interconnecting ductwork. Dimensions were not obtained for the BPH 3 mill system but would be considerably smaller than the above.

Bradley quotes the connected load for the large and small units as 940 hp and 65 hp respectively based on the above mentioned preferred maximum coal feed sizes.

Energy consumption is estimated to be 53-66 kWh/ton for the largest unit (12-15 ton/hr.) and 73-89 kWh/ton for the smallest unit (0.6-0.75 ton/hr.)
Maintenance costs are estimated by Bradley to be U.S. $0.29 ton based on the following estimated maintenance requirements:

- replace rollheads every 8,000 hours
- replace die ring every 16,000 hours
- replace plow plate every 8000 hours
- replace plows every 2000 hours

Bradley and Amvest have provided Stone & Webster with results of grinding limestone which showed 100% smaller than 11 microns and an average size of 2.3 microns. They claim no problem in preparing micronized coal. They are scheduled to test grind a sub-bituminous coal to an average size of 8 microns maximum in January, 1988.

Micronized grinding installations to date include a BPH 3 mill pulverizing activated charcoal to 10 micron average size in Scotland and a BPH 30 mill pulverizing talc to 3 micron average size for a customer in Georgia.

4.7 Kennedy Van Saun Ball Mill

KVS of Danville, Pennsylvania, manufactures a wide range of dry and wet grinding mills for a wide range of industrial applications. They were contacted as a result of previous Stone & Webster studies involving wet grinding to produce micronized coal.

KVS stated that the ball mill is not capable of producing 98% minus 325 mesh with dry grinding but should be capable of producing 95% minus 325 mesh on a coal of HGI 50. This grind could be achieved in a closed circuit direct fired configuration including a single ball mill with an external classifier of the twin cone type incorporating outlet vanes, generally as shown in Figure 4.7.1. The recycle ratio would be 2-3:1 for an HGI of 50.

Mill capacities range from 200-300 lb./hr. to approximately 48 ton/hr. for a micronized grind, the horsepower range being 15-2500 hp. These capacities would be doubled for producing standard pulverized grind.

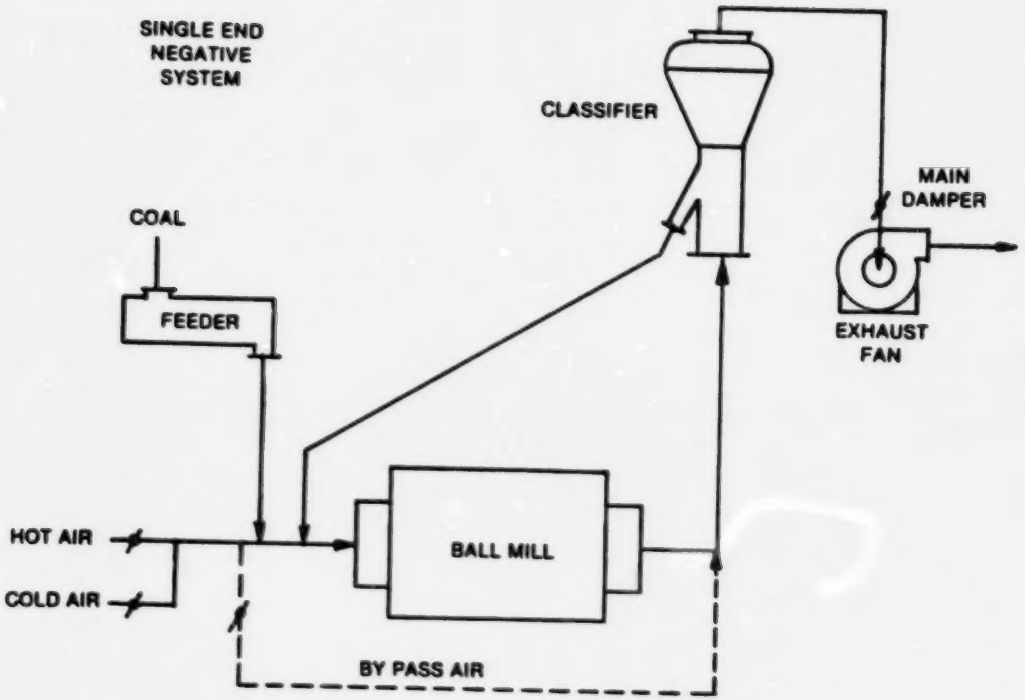


Figure 4.7.1 KVS Ball Mill System

Energy requirements in terms of specific energy consumption is approximately constant for all mill sizes at about 42 kWh/ton for 95% minus 325 mesh according to KVS.

The above capacities and energy consumption are based on a coal feed size of 1½" x 0. The mill can accept 2" x 0 but this would involve some capacity derating. The mill operates under negative pressure with an air/solids ratio of less than 2:1.

The pulverizer system shown in Figure 4.7.1 is the configuration used for small mill applications. For large mills, KVS uses a double ended mill with two twin cone classifiers. Typical physical dimensions for the smallest mill are 0.98 m x 1.52 m long with 0.69 m diameter classifier and for the largest mill 4.12 m x 5.8 m long with 3.05 m diameter classifiers.

To date, KVS have not done any dry grinding micronized coal tests. The information provided by KVS is therefore best estimate based on experience with standard pulverized grind coal and other substances. KVS have supplied dry grinding ball mills for coke firing of kilns in the cement industry in Canada. Product size for these applications was given as 100% minus 88 micron. While KVS has been heavily involved in research and development of wet grinding systems for coal/water slurry preparation, they have no current plans to develop dry grinding micronized coal technology.

4.8 RMD Opposed Jet Attrition Mill

The existence of this mill was discovered following discussion with Coaltech-Farrier regarding their Majac coal opposed jet attrition (COJA) mill. Coaltech-Farrier no longer manufactures the mill but informed us that Richard Dunbar (RMD Industries) is currently developing a fluid energy mill based on the COJA principle.

RMD Industries Inc. of St. Paul, Minnesota, is a small company engaged in the design, development and manufacture of a fluid energy mill derived from the Majac mill design. Majac is a generic name for the mill originally designed and built by Donaldson Industrial Group of St. Paul, Minnesota. The patent on the mill expired several years ago. The general principle of the mill is shown in Figure 4.8.1.

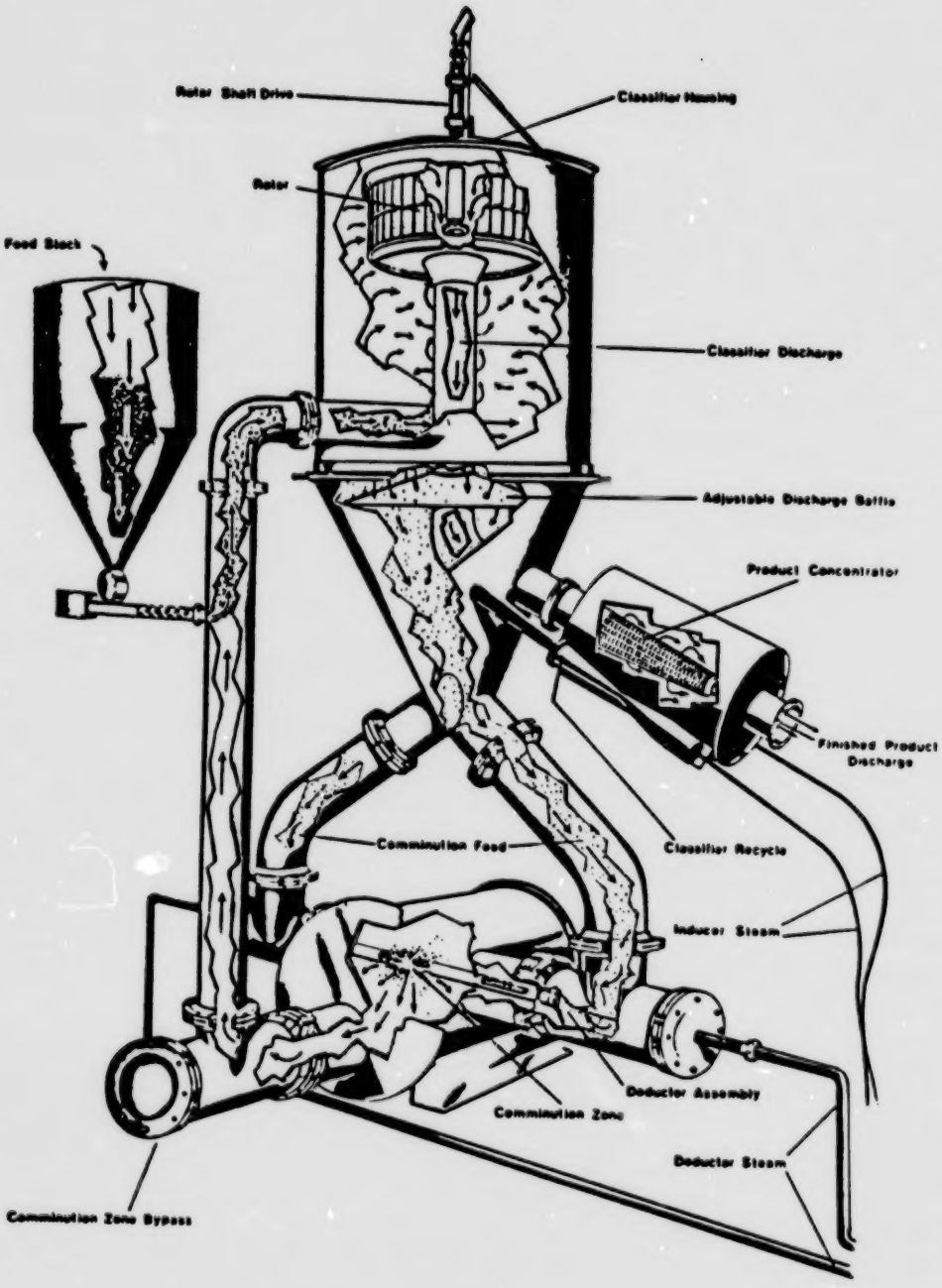


Figure 4.8.1 General Principle of the Coal Opposed Jet Attrition Mill

The mill grinds by true attrition with one stream of coal particles. The mill grinds and classifies the coal in a continuous operation by incorporating a spinning classifier assembly external to the comminution zone. Oversize particles are returned for further grinding. Steam or air can be used as transport medium. The COJA mill is not a new design and was used in the late 1940's to grind coal for pulverized coal fired heaters.

For micronized coal (98% minus 325 mesh) combustion applications, RMD is actively pushing steam as transport medium since product size consistency is better than with air grinding in addition to being inert for greater safety. RMD also claim a higher heat release rate with steam compared to air grinding when a hot air supply is required for coal drying purposes. The mill is intended as a direct fired type with no disengagement of the steam. This requires modified burner design since combustion air must be supplied as secondary air. Accordingly, RMD is currently investigating combustor design and development possibilities with Cohen and others with a view to offering a complete package for micronized coal firing. The need to provide supplementary fuel firing when using steam as transport medium remains a question to be resolved.

RMD has also held discussions with Foster Wheeler, U.K. regarding burner development and the possibility of F.W. becoming the European licensee for the mill/burner package. F.W. have a burner test facility at Hartlepool. RMD have a test plant in Twin Cities, Minnesota.

Mill capacities range currently from 500 lb./hr. to 2 ton/hr. equivalent on coal. RMD believe scaling up to 10 ton/hr. would present few problems. The required coal feed size is ¼" x 0. RMD claim that superheated steam consumption would be 0.62-0.68 lb. per lb. coal. No further technical information is available at this time as the mill in under development.

In the course of investigation into the RMD mill it was learned that the Atlantic Mining Corporation in St. Paul, Minnesota, in cooporation with Sterner Industries were also developing a COJA mill for mining industry capable of producing a micronized grind using air as transport medium. The mill is currently under development and is due to undergo initial trials during the first half of 1988. Although designed initially for mining applications, the mill may be adaptable to

micronized coal grinding in the future given the appropriate incentive.

4.9 Small Scale Pulverizer

In addition to a technical assessment of commercial scale pulverizers, the study remit requires identification of a small scale micronized coal pulverizer capable of producing 98% minus 325 mesh coal at a controlled rate of 50-200 kg/hr. (100-450 lb./hr.) and preferably with the capability of varying particle mean diameter between standard pulverized grind (75% minus 200 mesh) and micronized grind by adjustment of mill operating parameters. Other conditions are that the raw coal feed will be 100% minus 7 mm (¼") with a moisture content of approximately 2% and that the ground coal be transported to the burner ideally at an air/solids ratio of 2:1.

From the preceding sections, there are four pulverizers capable of producing a mirconized grind with a rated capacity of 1 ton/hr. or less. Table 4.9.1. presents a summary of pertinent data for these mills including an order of magnitude estimate for the installed cost of each mill in Canadian dollars. The CP Coal Mills pulverizer is excluded because the smallest unit is 2.5 ton/hr. and the KVS ball mill, which cannot meet the strict definition of micronized coal, is likewise excluded. The RMD mill is also excluded as it is under development and too little information is available at this time.

The following comments on each of the four possible pulverizers are pertinent to a small scale experimental application only in light of the above specific requirements and should not be construed as necessarily pertaining to commercial scale units.

The performance of the Ergon fluid energy mill is likely to be more marginal for small scale applications. While it can produce a micronized grind, energy requirements increase disproportionately for small units, as indicated in Section 4.5 and the fluid dynamics are more critical. The smallest size of Ergon mill using either steam or air is approximately 450 kg/hr. (1000 lb./hr.). The turndown capability of the unit is unlikely to be very high in this size range without adversely affecting the air/solids ratio. In addition, the ability to produce a consistent product at turndown with a stationary classifier could be another limitation. Although the advantages of simplicity, low wear and low maintenance are attrac-

tive, the only mill parameter which can be altered is the fluid energy input (flow and temperature) and use of the Ergon mill for experimental work could be somewhat limited. Other important considerations are:

a) For steam grinding, a source of highly superheated steam is required coupled with customized burner design in the combustor/boiler.

b) For air grinding, achieving a true micronized grind may be more difficult according to Ergon who indicate 96-97.5% minus 325 mesh.

The ability of the TAS downflow hammermill to produce micronized coal is uncertain and appears to depend heavily on the coal properties. The mill has been widely used in industry, doubtless because of its relative simplicity, low cost and ease of repair (rotor replacement in about five hours), but user operating experience varies widely in terms of the energy required to produce the specified grind. Because the mill is not equipped with a classifier, it operates on a once-through basis for both coal and air. Where the fan and rotor are driven off the same shaft, rotational speed is the only means for adjusting mill output and product consist. As components wear, therefore, rotational speed and hence energy input can be expected to increase to maintain the required particle size consistency. The mill would need to be designed for the worst case coal in terms of motor sizing in order that available energy input would not become a limiting factor.

The Bradley and Williams roller mill systems are both mechanical grinding semi-direct type and similar in operation. While the 7:1 air/solids ratio required by the Bradley mill could be a concern in commercial applications, grinding high moisture coal, this ratio should not increase the risk of explosion for pre-dried coal requiring a mill air temperature below 250°C (480°F). Both mills have separate control of grinding roller speed and classifier rotational speed which should give good control of particle size and allow some variation in mass mean diameter for experimental work. Both have good turndown capability, limited only by the minimum conveying velocity; Williams literature claims almost infinite turndown while maintaining product size. Fast response to load changes while maintaining product size has been demonstrated by Idaho Supreme Potatoes Inc. using the Williams semi-direct pulverizer system at its Firth, Idaho plant. To date, the Bradley mill is untested on micronized coal but

should demonstrate this capability during the scheduled tests in January 1988. The Williams mill has an established commercial operating history on micronized coal and would appear to be an excellent choice for experimental work.

TABLE 4.9.1

COMPARISON OF SMALL SCALE PULVERIZERS

Mill	Smallest Rated Capacity (kg/h)	Energy to Grind to 98% Minus 325 Mesh (1) (kWh/ton)	Predicted Turndown Capability (2)	Predicted Ability to Vary Particle Size	Approx. Installed Cost - Cdn. $ (See Note 3)	Approximate Maintenance Cost (Cdn.$)
Bradley Roller Mill	550	73	Good	Good	314,000	0.38/ton
Ergo Fluid Energy Mill						
- Air	450	150(4)	Poor	Poor	377,000 (5)	0.22/ton
- Steam	450	1.0 kg steam per kg coal (4)	Poor	Poor	377,000 (5)	0.22/ton
TAS Downflow Hammermill	550	30 (6)	Fair (225 kg/h)	Fair	93,000	0.38/ton
Williams Roller Mill	900	52.9	V. Good	Good	350,000	0.26/ton

Notes:

(1) Based on ¼" x 0 coal feed size.

(2) Based on ability to maintain normal air/solids ratio and particle size consistency.

(3) Order of magnitude only. Cost includes materials, installation and freight allowance. All taxes and duties extra. Mill cost includes estimate for coal feed bin and feeder. Bradley and Williams include a cyclone and a product air fan.

(4) Includes 25% allowance for small scale unit per Ergon estimate.

(5) Does not include cost of air compressor or steam source.

(6) TAS figure. User experience indicates could be 2-3 times this figure.

5.0 ECONOMIC EVALUATION OF DRY MICRONIZED COAL PULVERIZERS

This section presents an evaluated cost for each of the seven pulverizers in this study based on data provided by the vendors for commercial scale units.

Table 5.1 summarizes the equipment data provided by the vendors. Since some pulverizers are under development, particularly in regard to micronized coal applications, information is presented for which recent data is available and this covers a range of mill sizes from 2 to 30 ton/hr. The evaluation makes no allowances for economies of scale. The energy to crush coal from a feed size of 2" x 0 to the preferred feed size of ½" or ¼" is generally in the range of 0.75 to 3.7 kWh/ton; an average figure of 2 kWh/ton has been used where appropriate.

All costs are in 1987 Canadian dollars. The installed cost includes material and installation costs and an allowance for freight charges. Equipment material prices are obtained from vendors in U.S. dollars and have been converted using an exchange rate of $1 U.S. = $1.33 Cdn. Installation costs are based on a percentage of the material costs, either as recommended by the vendor or, where not provided, as estimated in-house. As per Note 6 in Table 5.1 it has been assumed that 70% of the installation cost would be by Canadians at a labour rate numerically equal to that in the U.S. (i.e. the exchange rate has not been applied to the Canadian portion). Where partial pulverizer system costs only were supplied by vendors, allowances for the balance of equipment, such as coal feed bin and feeder, have been added so as to compare the pulverizer systems on an equivalent footing. Each pulverizer includes the equipment indicated for direct or semi-direct firing in Figures 4.1 and 4.2 as appropriate.

Pricing information from Ergon did not include the cost of air compressors or steam source. A price for air compressors was obtained from Ingersoll-Rand sized on the basis of an air/solids ratio of 2:1. The supply and installation cost for the air compressors is difference between the installed cost for the air and steam grind alternatives shown in Table 5.1.

Table 5.2 presents the evaluated costs in terms of total cost per ton (2000 lb.) of micronized coal. The following economic parameters were used in the evaluation:

TABLE 5.1

GRINDING EQUIPMENT DATA

Mill	Capacity (tons/hr)	Feed Size	Energy to Grind to 98% Minus 325 Mesh	Installed Cost (6)	Maintenance Cost ($/ton)	Royalty Cost
Bradley Roller Mill	15	1-3/4" x 0	66 kWh/ton (1)	$1,504,000 (7)	0.38	N/A
Williams Roller Mill	8	2" x 0	50.3 kWh/ton	$ 943,000 (8)	0.26	N/A
TAS Downflow Hammermill	10	2" x 0	30 kWh/ton (2)	$ 271,000 (9)	0.38	N/A
CP Coal Mills Centrifugal/ Pneumatic Mill	10	2" x 0	28 kWh/ton	$ 780,000 (10)	0.33	N/A
Ergon Fluid Energy Mill						
- Air	20	1/4" x 0	122 kWh/ton (3)	$2,156,000	0.22	
- Stream	20	1/2" x 0	0.8 lb.steam/lb.coal + 2 kWh/ton (4)	$ 728,000 (11)	0.22	$1.50/ton (15)
KVS Ball Mill	30	1-1/2" x 0	42 kWh/ton (5)	$2,825,000	1.00 (12)	N/A
RMD COJA Mill	2	1-1/4" x 0	0.68 lb. steam/lb. coal + 2 kWh/ton (4)	$ 124,000 (13)	0.50 (14)	N/A

N/A = Not Applicable

TABLE 5.1 (Cont'd)

GRINDING EQUIPMENT ROOM

NOTES:

(1) Does not include energy to crush coal from 2" x 0 to feed size. This would be negligible.
(2) TAS figure. User experience indicates could be 2-3 times this figure.
(3) Includes energy to grind to recommended feed size estimated at 2 kWh/ton.
(4) Energy to grind to recommended feed size.
(5) Energy to grind to 95% minus 325 mesh maximum.
(6) 1987 Canadian dollars including cost of materials, vendor estimate of installation cost and allowance for freight. Taxes and duties extra. Exchange rate for U.S. supplied material and labour, $1 U.S. = $1.33 Cdn. Installation labour assumed 70% Canadian, 30% U.S. Ducting to and from the pulverizer system, foundations and support steelwork are excluded.
(7) Includes mill c/w drive and integral classifier, dual cyclones with rotary valves, material handling fan, product air fan, coal feed bin and coal feeder.
(8) As for (7) except single cyclone only.
(9) Includes mill c/w single motor for rotor and internal fan drive, coal feed bin and coal feeder.
(10) Skid-mounted, pre-wired microfuel system and coal feed bin and feeder.
(11) Air grind alternative includes fluid energy mill, coal feed bin, feeder, air compressors c/w motor drives and accessories. Steam grind includes the mill, coal feed bin and feeder but excludes the cost of the steam supply system and costs associated with customized burner design.
(12) Estimated price based on 60 ton/hr standard grind mill equivalent to 30 ton/hr. 95% minus 325 mesh. Price includes mill, drive, fan, classifier, motors, coal feed bin and feeder.
(13) Includes mill c/w classifier, coal feed bin and feeder but excludes steam supply system and costs associated with customized burner design.
(14) Estimated since no operating data available. Wear is a major concern with this mill.
(15) Nominal royalty is Cdn. $1.50/ton. Actual royalty is based on plant capacity.

a) Levelized annual real fixed charge rate of 10% based on amortization over 30 years. This is based on the figure of 9.6% developed by the Electric Power Research Institute (EPRI) in 1985 for use in power plant technical evaluation studies.

a) Energy costs:

- Electricity @ $0.05/kWh.

- Steam (Ergon and RMD) @ $4.41 per 1000 lb./hr. steam based on coal HHV of 12,000 Btu/lb., boiler efficiency of 85% and a delivered coal price of $75/ton. The coal price is an average of U.S. and Western Canadian coal prices delivered in Ontario.

c) Replacement cost of steam of $5 per lb./hr. steam per year. This is a capital allowance applied to the Ergon and RMD steam grind mills for the capital expenditure to increase boiler capacity. The Ergon mill requires 32,000 lb./hr. steam and the RMD mill, 2,700 lb./hr. The additional levelized annual fixed charges are:

Ergon - 5 x 32,000 x 10% = $16,000
RMD - 5 x 2,700 x 10% = $ 1,400 (rounded)

d) Annual capacity factor of 0.9, equivalent to operating the mill for 7884 hours per year at rated capacity.

Annual electric energy costs and steam energy costs were obtained by multiplying the energy requirement per ton (from Table 5.1), the unit energy price, the ton/hr. and the operating hours per year. Similarly, annual royalty costs in the case of the Ergon mill were obtained as the product of annual coal quantity and unit royalty ($1.50/ton). No real escalation was assumed for any of the cost elements, the assumption being that each element would follow the general rate of inflation.

The energy cost for preheating the air to the air grind mills for coal drying is not included since mill air temperature depends upon the raw coal moisture content and the air/solids ratio within the mill. The total energy, however, will be similar for all the air grind mills and would not significantly impact on the relative ranking, although the total unit cost/ton of coal will increase. The increase is estimated to be

TABLE 5.2

GRINDING COSTS

Mill	Levelized Annual Fixed Charges ($)	Annual Electricity or Steam Cost ($)	Annual Maintenance Cost ($)	Annual Royalty Cost ($)	Total Annual Cost ($)	Total Units Cost ($/ton)
Bradley Roller Mill	150,400	390,300	45,000	N/A	585,700	4.95
Williams Roller Mill	94,300	158,600	16,400	N/A	269,300	4.27
TAS Downflow Hammermill	27,100	118,300	30,000	N/A	175,400	2.22
CP Coal Mills Centrifugal/ Pneumatic Mill	78,000	110,400	26,000	N/A	214,400	2.72
Ergon Fluid Energy Mill						
- Air	215,600	961,900	34,700	236,500	1,448,700	9.19
- Steam	88,800 (1)	1,112,600	34,700	236,500	1,472,600	9.34
KVS Ball Mill	282,500	496,700	236,500	N/A	1,015,700	4.29
RMD COJA Mill	13,800 (1)	94,600	10,000	N/A	118,400	7.51

NOTES:

(1) Including allowance for replacement cost of steam - Ergon $16,000, RMD $1,400.

approximately $0.90/ton for a mill air temperature of 400°F (205°C).

As indicted in Table 5.1, the TAS mill energy requirement is likely to be considerably higher in practice for a coal HGI of 50 than the 30 kWh/ton claimed by the vendor. For example, if the grinding energy increased 2.5 times, as user experience would indicate, then the total unit cost would become $4.48/ton which is very similar to the other mechanical grinding mills, i.e. Bradley, Williams and KVS.

The evaluated cost of the Ergon steam fluid energy mill does not include the cost of the steam source and, therefore represents the case where steam is available at the site. For a grass roots facility where steam is not available, the total unit cost would increase.

6.0 REVIEW OF MICRONIZED COAL COMBUSTION TECHNOLOGY

The conventional specification for pulverized coal fuels, generally defined as 80% passing 200 mesh U.S. Standard Sieve (74 microns), sets a performance standard for pulverizers. This fuel quality enables large boilers to be operated under safe firing conditions and with reasonably steady heat outputs. Practical results assembled over time have resulted in improved knowledge of heat transfer, slagging and fouling of heat exchange surfaces and other factors so that improvements in boiler design, and in the size of boiler units were possible. It was demonstrated that pulverized coal firing was applicable to virtually every type of coal and that there is virtually no upper constraint on boiler size if coal feeding and pulverizing units and burners can be physically accommodated. Boilers of 1300 mW unit size are being operated successfully and larger units are feasible.

However, these developments have largely ignored certain other factors that were long suspected to have significant effect on combustion performance and boiler operational. Thus, pulverizers are sited directly alongside boilers and coal fed to them is blown directly via the burners into the furnaces. This arrangement makes it difficult to examine the actual condition of the pulverized coal as fired, including its size distribution and the quantity of oversize material. It was customary to assume that if firing difficulties were encountered, the probable cause lay in transient variation in coal quality, e.g. ash, rather than in the physical condition of the pulverizer product, even though it was known that the burning behaviour of coal particles varied substantially as sizes decreased from 200 mesh to zero and that carbon losses increased significantly as the amount of oversize increased.

The first comprehensive attempt to investigate this situation was reported in 1957 [1]. The work included an assessment of the effects of particle sizes on the behaviour of dust clouds; of particle sizes and burning rates; of particle sizes and residual ash particle sizes; and on combustion trials in an experimental open hearth checkerwork assembly at a steel plant. It also reported on side by side trials in two identical industrial boilers, both fitted with Majac Jet Pulverizers capable of producing coal grinds at up to 30,000 lbs. per hour, with variable size distributions up to 90% passing 325 mesh (45 microns), hence

approximating to the present definition of micronized coal.

The basic relationships of particle size with diameter, relative mass and free falling velocities in still air are summarized in Table 6.1. Relative particle masses are obtained by raising diameters in microns to the third power, this relationship being applicable to cubes or spheres. The fourth column sets out relative falling times in still air over a fixed distance, assuming a specific gravity of 1.5 for coal and applying Stokes Law. Calculated times are based on terminal velocities. It was concluded from these relationships that the tendencies for particles to fall out of dust streams increases very rapidly as sizes increase beyond 200 mesh, hence supporting the basic specification for pulverized fuel. Conversely, particles tend to approach gaseous behaviour and to follow gas stream flow patterns more and more closely as sizes decrease from 200 mesh and maintain this behaviour even at low furnace gas velocities.

Consideration of particle surface area and particle size also show that major effects occur as size is decreased below 200 mesh, increases in area becoming particularly significant below 20 microns (sub-sieve), as shown in Figure 6.1. To the extent that combustion rates are dependent on surface areas, as one of the rate controlling variables, it is obvious that large increases can be expected for micronized grinds compared with standard pulverized grinds. The effect of more rapid combustion would be to reduce the flame lengths, as illustrated schematically in Figure 6.2.

It is reasonable to assume that, in the absence of agglomeration, smaller coal particles will produce even smaller ash particles and that these will remain in suspension in the furnace gases, will follow streamlines and will exit with the flue gas leaving the furnace convection passes, hence greatly reducing the fouling and slagging properties often associated with conventional pulverized fuel firing. See Figure 6.3.

The firing trials reported by Bayles [1] largely confirmed that these advantages of firing micronized coals were obtainable.

More recently, since 1979/80, a number of laboratory and large scale demonstration tests of the concept of using dry, micronized coal as substitute fuel in boilers designed for oil or natural gas firing have been sponsored by various organizations in the United

States, including the Institute of Gas Technology (IGT), Gulf States Utilities (GSU) and Mississippi Power and Light (MP&L). Typical differences in the design parameters of coal, oil and gas fired boilers are illustrated in Figure 6.4. [2, 3]

NECUP, an acronym for North East Coal Utilization Programme, initiated by a group of New England Utility companies interested in advancing technologies that would permit the burning of coal in power boilers designed primarily for oil firing, also support a programme intended to validate, through "proof of concept testing," that the combustion advantages of ultrafine ground pulverized coal can be successfully combined with the convenience of coal-water mixture fuel. This programme has also received sponsorship from other Atlantic, Pacific and Gulf coast utilities and other interested organizations, such as New York State Energy Research and Development Agency (NYSERDA), U.S. Department of Energy/Pittsburgh Energy Technology Centre (DOE/PETC). However, as previously noted, this present study is limited to the consideration of dry grinding and firing systems.

For the combustion tests performed at the IGT [4], a Pittsburgh No. 8 coal containing 7.24% ash was ground to three different size distributions, with mass mean particle diameters of 6.6, 18.1 and 41.0 microns. Ten combustion trials were conducted at firing rates and durations ranging from 1.6 to 2.5 X 10^6 Btu/hr. and 2 to 75 hours respectively. Analysis of solid and gas samples collected at various locations along the furnace axis were compared for the different grind distributions, as were differences in total radiant heat flux. Deposition rates were determined using a specially designed convective pass probe, which consisted of 2 in. OD gas cooled tubes located on 4 in. centres. Flue gas temperatures at the deposition probe were 2320-2370°F, while tube surface temperature varied from 640 to 1090°F.

Combustion intensity achieved with the finest ground coal was found to be more than twice that for the coarse ground coal, i.e., 0.9 X 10^5 Btu/hr.-ft^3. vs. 0.4 X 10^5 Btu/hr.-ft^3. Accordingly, flame length was determined to be sensitive to coal size distribution and was reduced by about 60% from the coarsest to finest grind fuel, Figure 6.2. Somewhat surprisingly, nitrogen oxide emissions did not appear to change with coal particle size distribution. Deposition rates on the convective pass probe were reduced by about 80% as

coal particle size was reduced from the coarsest to the finest distribution.

To investigate the technical and economic reliability of micronized coal as an alternate fuel, GSU sponsored a similar programme with the added objectives of determining if sootblowing could control ash deposition from micronized coal on tightly spaced superheater tube banks [7].

A full account of this work is provided in Appendix I but is summarized below:

Conventional and micronized grinds of three types of coal (one each from West Virginia, Ohio and Indiana), representing a range of ash contents and ash fusion temperatures, were evaluated. Ash deposition testing was performed in Babcock & Wilcox's (B&W) Laboratory Ashing Furnace (LAF), a 200,000 Btu/hr. test furnace designed to produce fly ash with properties similar to ash from a large utility boiler. The LAF was operated with a furnace exit gas temperature comparable to that of an oil designed unit (2400°F). The ash from each coal burned was collected and analyzed for particle size, carbon content and elemental ash constituents.

The size of fly ash particles from burning micronized coal were substantially smaller than those from conventional pulverized coal. Ash particles from the micronized coal did not agglomerate appreciably when these coals were burned in the LAF and these particles were small enough to travel with the flue gas around the simulated heat exchanger tubes, while pulverized coal ash particles did not, but instead impacted and deposited on the tubes [5].

Based on the successful results of the LAF tests, scaled-up tests were conducted in B&W's 4 million Btu/hr. Basic Combustion Test Unit (BCTU) using the same West Virginia Sewell No. 1 coal that was tested in the LAF. See Figure 6.5 [6]. A 64 hour around-the-clock combustion/ deposition test was performed using micronized coal. In addition, some limited testing was performed using a finer micronized coal (mass mean diameter of 8.3 microns as compared to 9.4 microns for micronized coal). For comparison, some testing was performed using conventional pulverized coal.

During these tests, the flame from conventional pulverized coal filled the entire BCTU furnace. When burning micronized coal the flame occupied about 75% of the furnace region. The flame from finely micronized

coal occupied about one-half of the furnace length. These results are similar to those obtained at IGT and are shown in Figure 6.2. In addition, as was found in the IGT tests, nitrogen oxide emissions did not appear to change as coal particle size was reduced.

Five parametric combustion tests using conventional pulverized coal were planned to be conducted prior to the full power deposition test with sootblowing. However, before these could be completed, the deposition test section plugged with ash. This occurred within seven hours after starting up on pulverized coal. Tube (surface metal) temperatures during this period ranged from 400 to 600°F as compared to 950-1000°F when at full power.

In contrast, when micronized coal was fired, the deposits formed on the tightly-spaced tube bank in the BCTU were removed by sootblowing with air. During this 64 hour continuous test, tubes were blown at intervals of one to three hours and base deposits (deposits on the tubes immediately after sootblowing) did not appear to increase with time. Longer duration demonstration testing in full size boilers is required to confirm these test results and address the question of erosion. Detailed plans for such scaled-up testing were evaluated.

Mississippi Power & Light Company (MP&L) and Ergon, Inc. recently completed a programme to demonstrate the feasibility of firing Coal/Steam (C/S) mixtures in a utility boiler designed for natural gas firing. [8] Coal/Steam is the dry micronized product of the Ergon Micropulverizer (a patented fluid energy attrition pulverizer) entrained in steam when steam is used as the working fluid. The programme consisted of two phases. The first phase consisted of firing C/S in a test rig. Since this was successful, the programme continued into the second phase for firing C/S in a utility boiler and MP&L's Delta Steam Electric Station (DSES) Boiler 1 was selected. DSES was designed and installed during the early 1950s and consists of two identical units, each designed to fire natural gas or oil to produce steam that drives two turbine generator sets of 99 mW capacity each. Each of the two boilers installed was designed to burn natural gas or fuel oil while generating 900,000 lb of steam per hour at 1550 psi and 1005°F at the superheater outlet. This boiler contains 12 burners (two rows of six). Four Foster Wheeler (FW) intervene coal burners were installed (next to each wall burner on the top and bottom rows) for the purpose of firing C/S. Ten thousand tons of

East Kentucky bituminous coal (see Table 6.2) was used in this demonstration.

In Phase I, C/S mixtures were successfully fired in a test rig at Ergon Inc.'s Vicksburg facility. The primary objective of the Ergon facility test programme was to obtain pertinent information regarding C/S combustion and pulverizer performance characteristics. The information obtained from this test programme was necessary to precisely define the hardware and operational requirements to successfully implement C/S firing at MP&Ls Delta Steam Electric Station. The test rig consisted of an insulated open-ended partially covered roof combustion chamber, a FW intervene burner (which was subsequently used as one of the four installed at DSES), C/S feed line from an Ergon fluid (steam) energy micropulverizer to the FW burner and a forced draft fan providing combustion air (heated via steam coils inside ducting below the combustion chamber) to the burner.

Water-gas type flames with 100% C/S firing were observed on several occasions during the test firing period. The water-gas flames were light yellow and transparent, i.e., the burner could be seen quite clearly through the flames.

Since the objectives of the test firing were successfully completed, the second phase, firing C/S in a utility boiler, was initiated. Prior to initiating C/S firing, a series of baseline tests firing natural gas, fuel oil and fuel oil and natural gas were conducted to obtain boiler performance and combustion characterization data for comparison with C/S firing data. Once baseline testing was completed, C/S firing was initiated.

This programme demonstrated that C/S mixtures could be fired with excess oxygen levels as low as 2% but oxygen levels of approximately 5% were required to maintain carbon carryover on the order of 1% (equivalent to less than 0.1% boiler efficiency loss). Such carbon carryover loss is lower than levels typically experienced with pulverized coal (PC) firing. Average ash particle size distribution levels were between typical PC firing and fly ash levels measured in laboratory micropulverized coal combustion tests. The calculated superheat type temperatures are 43°F higher for C/S at 850,000 lb/hr. steam rate prediction than the equivalent gas fuel type temperatures. They are, however, well below the 1263°F level calculated from

the maximum natural gas design data at 950,000 lb/hr. steam flow.

A thorough boiler inspection was conducted by MP&L subsequent to the C/S test programme and the following observations were noted:

- Little evidence of boiler tube erosion was found.

- The ash deposits on furnace and heat transfer surfaces were not excessive and were very friable, hence, easily removed. In general, these surfaces were found to be clean.

- The ash buildup on the furnace floor was substantial, indicating the need for a furnace bottom-ash handling system. Accumulation occurred during the tests due to ash falling from walls during load change (the wall buildup increased rapidly when fuel particle size was out of specifications).

- Ash buildup in localized sections of the finned tube economizer outlet and air heater indicated the need to install additional sootblowers in these areas.

MP&L subsequently retained KVB Inc. to model DSES Unit 1 via computer for the purpose of predicting boiler performance associated with a full-scale conversion of Unit 1 to C/S firing. [9] This modeling effort involved the use of two computer programmes: PEPSE (Performance Evaluation of Power System Efficiencies), which is a commercially available programme used by numerous utilities, industries and consultants; and KVB's Performance Evaluation Model. PEPSE was used to model the boiler for gas and oil fuel firing; however, a basic problem was encountered with using PEPSE for predicting C/S performance. Although PEPSE is capable of predicting performance with a variety of alternate fuels such as coal/water mixtures, it did not contain the flexibility for handling coal/steam mixtures. Specifically, the steam could not be treated properly in the combustion and efficiency calculations. As a result, the performance predictions were obtained with KVB's model. PEPSE was used, however, to verify KVB's model for gas and oil fuel and specific heat transfer parameters associated with C/S fuel.

The following are the basic stipulations corresponding to the C/S performance predictions:

- The micropulverizer can be designed to provide consistent C/S mixtures on the order of 1.07:1.0 steam to coal ratio on a weight basis, with coal particles micropulverized to less than 44 microns.

- A burner can be selected such that C/S autoignition is achieved (no auxiliary gas fuel required to maintain combustion). Such a burner should generate the temperature needed to produce water-gas type flames. The performance prediction will not be substantially affected if water-gas type flames are not produced within specification. The flame envelope should be very similar to oil flames and, hence, no limitation due to flame impingement would be anticipated.

- The carbon carryover can be maintained at less than 5%, equivalent to less than 0.5% boiler efficiency loss.

- The boiler heat transfer surfaces can be maintained free of ash deposition.

- The boiler feed pumps and water make up are capable of providing feedwater at rates up to 850,000 lb/hr. at design feedwater temperatures. It should be noted that feedwater temperatures measured during the DSES test programme were on the order of 30°F below design levels (the HP feedwater was out of service). Operation with the feedwater at these levels increases the predicted fuel and mass gas flowrates on the order of 3%.

A series of model sensitivity runs were made by individually varying each independent (input) variable in the model by a fixed percent. The errors associated with each independent variable were estimated and the model sensitivity runs were used to established the prediction accuracy of the various boiler performance parameters.

The performance predictions show that no performance deficiencies exist which would limit boiler load capability. The only potential load limiting condition may be tube erosion in the inlet superheater section. The gas velocity profile through this section is such that if the coal particles were characteristic of standard pulverized coal, the boiler would be limited to a steam flow of less than 725,000 lb/hr. to maintain gas velocities through this section at less than 75 ft./sec. The gas velocity through this section at full load (850,000 lb/hr. steam flow) is 90 ft./sec.

Micronized coal C/S gas products contain particles fine enough to follow the gas flow stream and hence erosion from particle impaction is expected to be minimal.

Based on the C/S test programme results, observations made during the programme and predicted performance with 100% C/S firing, it was concluded that conversion of DSES Unit 1 is technically feasible without load limitations.

Ultimately, the final decision will depend upon the economics involved. The cost of the above-mentioned retrofit considerations, combined with the costs of other items (e.g. an electrostatic precipitator) not mentioned, will dictate the economic feasibility of C/S conversion.

Other economic and engineering evaluations have since been performed to establish the merits of dry micronized coal conversion for units in the 100 to 150 mW size range and, depending on specific requirements at potential conversion sites, conditions may be obtained which would justify conversion of existing oil/gas fired units to dry micronized coal.

During 1983, GSU supported Stone & Webster Engineering Corporation in a joint study to determine the economic and technical feasibility of converting a 150 mW utility steam generator, originally designed to fire oil and gas, to micronized coal firing. The steam generator selected was the Unit No. 3 boiler at the Roy S. Nelson Station in Westlake, Louisiana. The study included assessment of the potential impact on the environment, including air quality, water/wastewater and solid waste disposal issues. It was concluded, on the basis of certain defined economic criteria, that the technical and economic feasibility could be demonstrated.

Since that time changes in electricity rate setting procedures in the United States and the major reduction in world oil prices after 1985 have greatly reduced funding levels for coal based R&D by the utility companies and further work on development of coal fired technologies, including micronized coals, has been largely suspended.

Some progress in micronized coal firing applications in the industrial steam sector has continued, almost entirely by private industry funding, which have already been described in Section 4.

TABLE 6.1

TABLE OF RELATIONSHIPS - COAL PARTICLES (1)

SIZE (U.S. Standard)	DIAMETER (Microns) (3)	RELATIVE MASS (1)	FALLING TIME (Seconds) (2)
10 Tyler 12	1,651	4,510,000,000	Less than 1
20	833	578,000,000	Less than 1
40 Tyler 35	417	72,400,000	Less than 1
60	246	14,900,000	1.09
80	175	5,360,000	2.19
100	147	3,175,000	3.12
140 Tyler 150	104	1,125,000	6.12
200	74	405,000	12.50
230 Tyler 250	61	227,000	17.50
325	43	79,500	35.00
Sub-sieve	30	27,000	75.00
Sub-sieve	20	8,000	175.00
Sub-sieve	15	3,375	312.50
Sub-sieve	10	1,000	675
Sub-sieve	5	125	2,750
Sub-sieve	4	64	4,375
Sub-sieve	1	1	67,500 (18 - 3/4 hrs.)

(1) Cube of diameter of largest particle in microns.

(2) Falling time for a given distance (10 ft.). Assumed density 1.5.

(3) 1 micron (μ) equals 0.001 mm or 0.0000394 in.

TABLE 6.2

TYPICAL MOISTURE, PROXIMATE, ULTIMATE AND SULFUR FORMS ANALYSES, CALORIFIC VALUES FOR COAL USED IN MP&L TEST

	East Kentucky Coal					
	Sample 1		Sample 2		Sample 3	
	As Received	Dry	As Received	Dry	As Received	Dry
Total Moisture Percent	4.9	-	8.8	-	-	-
Proximate Analysis, Percent						
Moisture	4.9	-	8.8	-	-	-
Volatile Matter	36.5	38.4	-	-	-	-
Fixed Carbon	50.3	52.9	-	-	-	-
Ash	8.3	8.8	-	-	-	-
Ultimate Analysis, Percent						
Moisture	-	-	8.84	-	-	-
Carbon	-	-	69.18	75.89	-	74.93
Hydrogen	-	-	4.48	4.91	-	5.14
Nitrogen	-	-	1.46	1.60	-	1.51
Chlorine	-	-	0.19	0.21	-	-
Sulfur	-	-	0.77	0.84	-	0.82
Ash	-	-	9.99	10.96	-	8.91
Oxygen (Difference)	-	-	5.09	5.59	-	8.69
Total	-	-	100.00	100.00	-	-

TABLE 6.2(cont.)

	Sample 2		Sample 3	
	As Received	Dry	As Received	Dry
Sulfur Forms, Percent as S				
Pyritic	-	-	-	0.18
Sulfate	-	-	-	0.01
Organic (Difference)	-	-	-	0.63
Total	-	-	-	0.82
Gross Calorific Value				
Btu/lb	12,859	13,522	-	-
Btu/lb Moisture And Ash Free	-	14,818	-	-

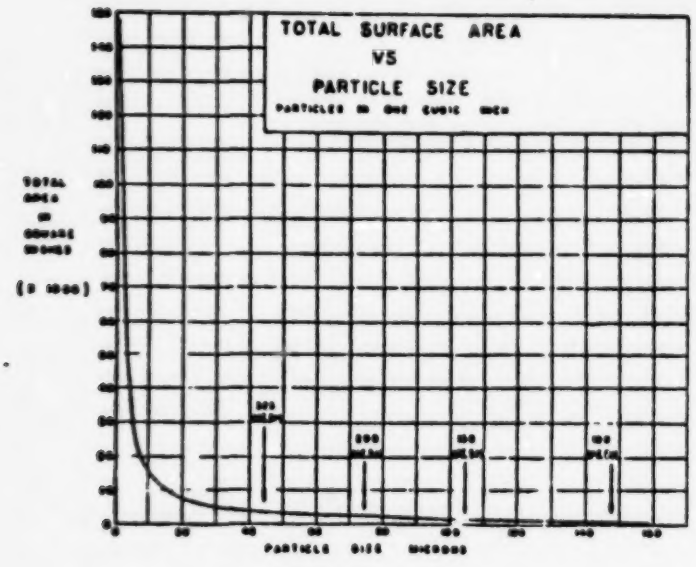
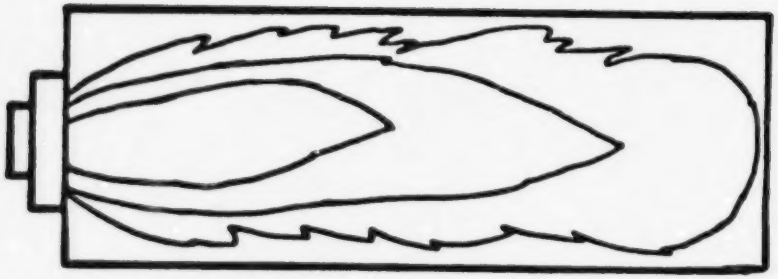


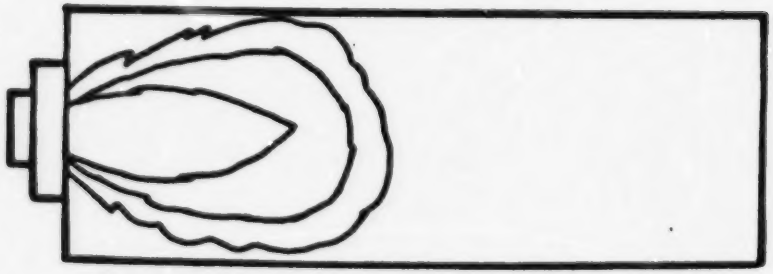
Figure 6.1 Total Surface Area Versus Particle Size (Linear)

COMPARISON OF FLAME LENGTH FOR PULVERIZED AND MICRONIZED COAL



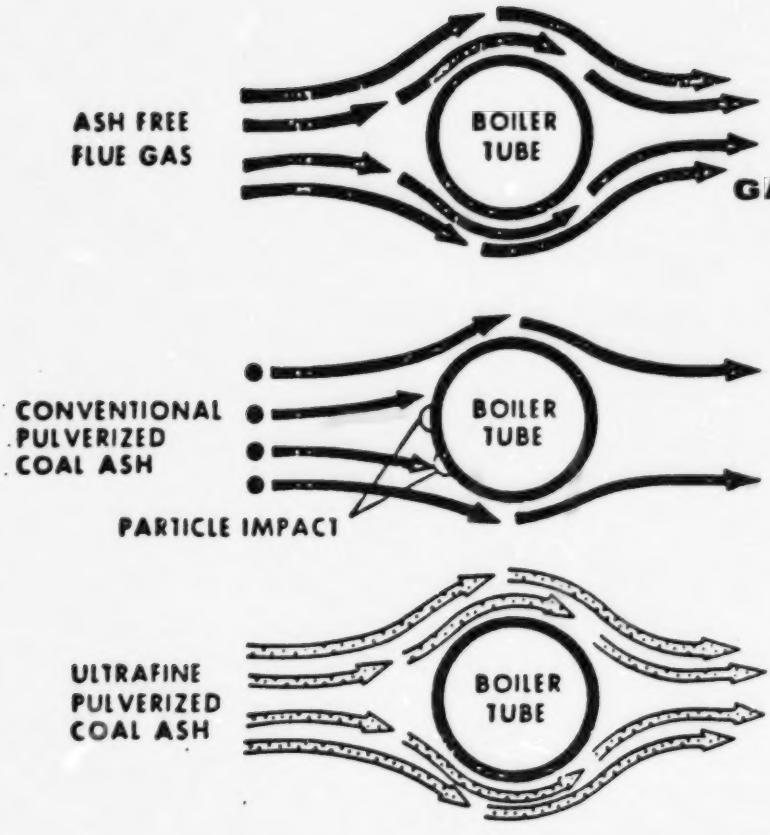
PULVERIZED COAL FLAME

MICRONIZED COAL FLAME



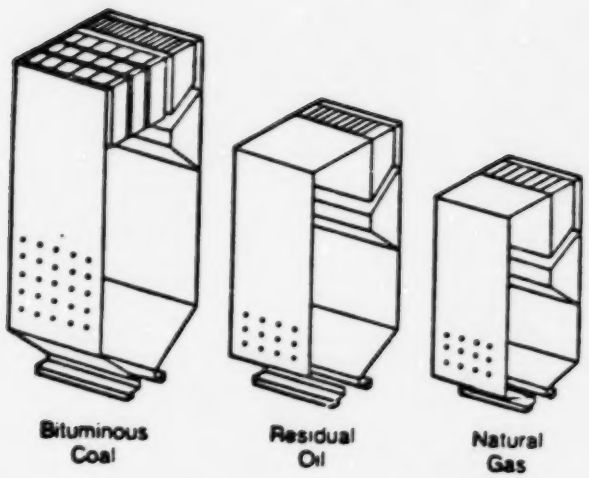
FINER MICRONIZED COAL FLAME

FIGURE 6.2



COMPARISON OF GAS AND ASH PARTICLE STREAMLINES WHEN FIRING CONVENTIONAL VS. ULTRAFINE PULVERIZED COAL

FIGURE 6.3



TYPICAL BOILER DESIGN DIFFERENCES

Fuel	Ash Content Typical		Heat Input 1000 Btu/hr-ft²				Clear Tube Spacing, Side to Side, in.	
	Weight Percent	lb/10⁶ Btu	Per Plan Area	Per Effective Projected Radiant Surface	Distance, Top Row Burners to Furnace Outlet, ft	Maximum Convection Pass Velocity, fps	Radiant Surface	Convective Surface
Natural gas (or distillate oil)	0	0	3000	200	20-30	100	2	2
Residual oil	0.15	0.08	2400	175	30-45	75	5	2
Bituminous coal	15	12	1700	100	45-70	50	8-14	4-6

FIGURE 6.4

MODIFIED BASIC COMBUSTION TEST UNIT

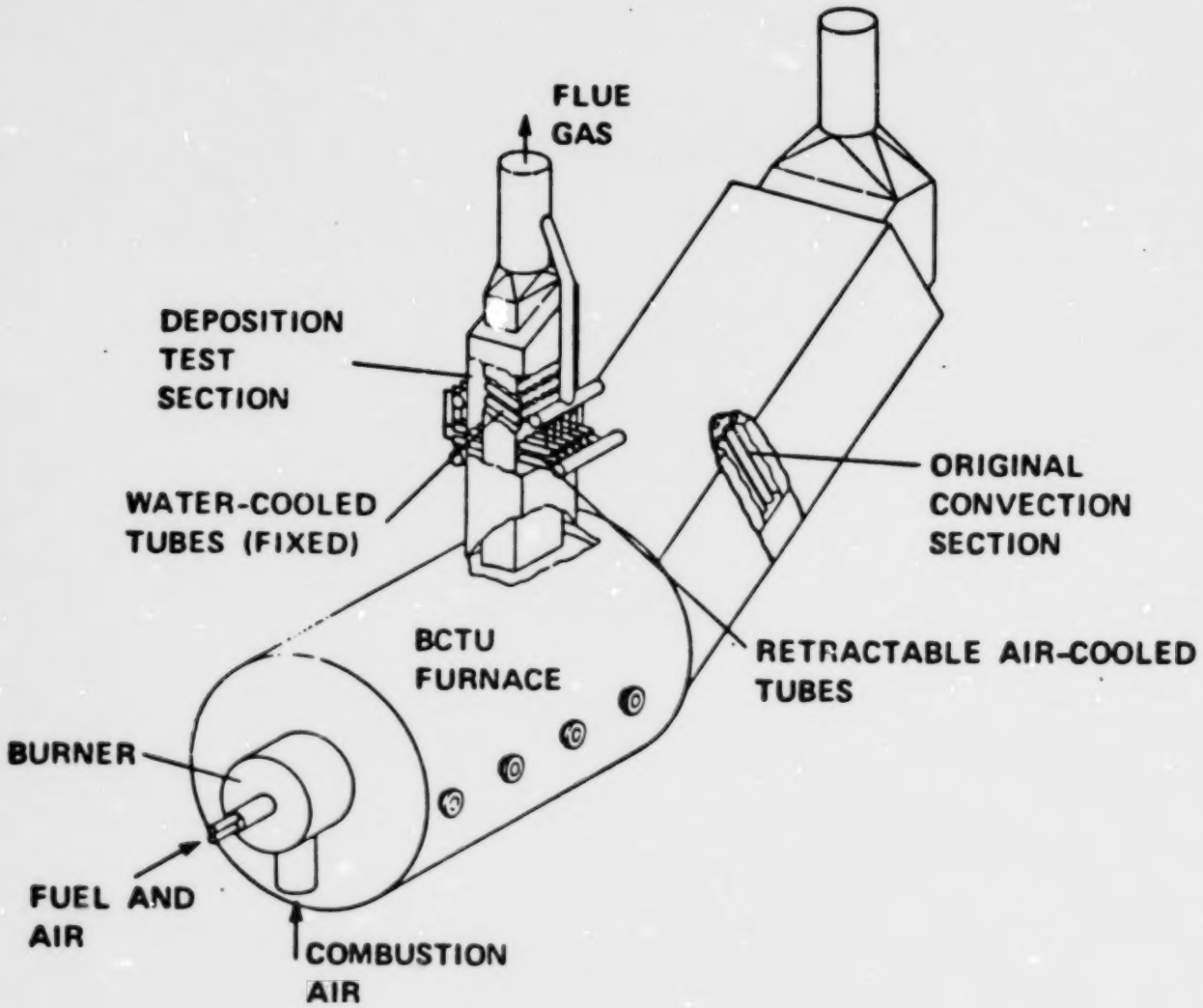


FIGURE 6.5

7.0 OBSERVATIONS AND DISCUSSION

1. It is evident from the information provided by the pulverizer vendors that relatively little research and development work has taken place specifically aimed at producing micronized coal for the range of coals used in industrial and power boiler applications. Documentation is needed regarding:

   - Ability to grind to micronized coal specification.
   - Energy requirements for micronized coal grinding.
   - Impact of coal grindability and moisture content on mill performance.
   - Capacity, availability and associated maintenance necessary to maintain micronized grind specification.

2. Pulverizer vendors are unlikely to undertake more definitive test work on micronized coal unless the appropriate incentive and market opportunities arise. Pulverized system development is occurring, however, for producing finer grinds for the mining and powder industries, which should be of benefit for micronized coal applications.

3. The TAS downflow hammermill appears to be capable of producing a micronized grind for soft coals but may be marginal for HGI 50 coal and harder.

4. Energy consumption and fixed charges are the major components of the total unit grinding costs.

5. With the exception of the KVS ball mill, maintenance costs were found to have a minor impact on the total annual grinding cost.

6. Based on the manufacturer's claims, the CP Coal Mills pulverizer is producing micronized coal at an energy consumption comparable to that required to prepare standard grind pulverized coal using conventional mechanical pulverizers. However, the energy consumption quoted by CPCM is for 92-95% minus 325 mesh and the claim that 98% minus 325 mesh can be achieved with classifier adjustment requires verification, as does the energy consumption to achieve this grind.

7. The Bradley and Williams roller mills and the KVS ball mill are all mechanical grinding systems and were found to have similar total unit costs. The TAS downflow hammermill is also a mechanical grinding mill and has the lowest total unit cost based on the vendor's claim for energy consumption. User experience indicates that for true micronized grind, energy consumption may be 2-3 times that claimed by TAS. If so, the total unit cost of the TAS mill becomes very similar to the other mechanical mills.

8. Fluid energy mills energy consumption does not decrease in proportion to coal with turndown-potential problem for combustor which requires essentially fixed air/solids ratio. Steam grind mills require customized burner design which may be costly and a disadvantage for large scale boiler applications.

9. Scale-up of all mills would appear to present no major difficulties according to the vendors. Appropriate incentives are required, however, for larger mill sizes to be developed.

10. Ergon royalty payment has a significant impact on total unit cost. In a competitive bidding situation, the actual royalty may be reduced.

11. A number of installations of micropulverizers at industrial steam plants have been made in recent years that were commercially intended and for which detailed performance data is not readily available. The most comprehensive report available for an industrial boiler refers to a conversion project at a plant in North Wales, U.K. [17], which incorporates a fluid energy, coal-steam micronizing mill feeding a 90,000 lb. per hr. water tube boiler designed for oil firing. During a 14 month proving trial the unit advanced from being a manually controlled base load, prototype plant to an automatically-controlled, load following unit that demonstrated the higher combustion rates and lower fouling characteristics expected from micronized coal firing.

12. Several electric utilities in the U.S. have indicated interest in converting oil or gas designed boilers to micronized coal firing and a number of research and development programmes have been completed. The trials, carried out in the period 1980 - 1984, culminated in conversion of a

100 mW, gas fired boiler to partial micronized coal firing, the fuel being prepared in a steam operated fluid energy mill [9] burning 10,000 tons of bituminous, East Kentucky coal. Based on the test programme results it was concluded that conversion of the unit to full micronized firing was technically feasible without load limitations.

13. The work reported to date has not indicated that any major changes in NO_x emission results from firing micronized coal. In view of the higher combustion intensities achieved with the micronized fuel this observation is somewhat surprising. However, NO_x emissions are known to be influenced by the burner design and this posibility merits additional investigation. In the case of sulphur dioxide emissions, grinding the coal to finer sizes may liberate more pyritic sulphur as discrete particles but, given the close coupling of grinding and burner systems, does not significantly reduce the total sulphur in the fuel feed to the boiler. Unless some methods are introduced to separate the additionally liberated pyrites, the introduction of micronized coal firing can have no impact on SO_2 emissions. Micronizing has been shown to increase the quantities of fly ash leaving the boiler but current indications are that the equipment available for removing and controlling particulates will be suitable if the necessary unit capacities are provided.

The question whether micronized firing will enable other emissions control techniques to be improved e.g. sulphur sorbent injection, requires additional research.

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LISTING OF COMMUNICATIONS WITH
MANUFACTURERS OF MICRONIZING MILLS

1. William Patent Crusher and Pulverizer Company 2701 North Broadway, Mo., USA 63102. Tel. 314-621-3348 Carl Rehmer, telefax dated October 15, 1987.

2. C.P. Coal Mills Inc., 802 2nd St., Coralville, Iowa, USA 52241. Tel. 319-351-5404 Allen C. Wiley, telefax dated October 19, 1987.

3. Bradley Pulverizer Company, 123 S. Third St., P.O. Box 1318, Allentown, Pa., USA 18105. Tel. 215-434-5191 David J. Fronheiser, telefax dated October 19, 1987 and telephone communication November 24, 1987.

4. Ergon Inc., P.O. Drawer 1639, Jackson, Mississippi, USA 39215. Tel. 601-948-3472. Don Selles, telefax dated October 19, 1987 and telephone communication October 27, 1987.

5. TAS Corporation, P.O. Box 68, Magna, Utah. Tel. 801-250-2908 Chad White, telephone communication October 27, 1987.

6. Howden Group Canada Ltd., 1510 Birchmount Road, Scarborough, Ontario M1P 2G6. Tel. 416-752-7310 Ray Brooks, telephone communication October 27, 1987.

7. RMD Industries Inc., St. Paul, Minn. Tel. 612-331-7777 Dick Dunbar, telephone communications November 6 and 27, 1987.

8. Coaltech Farrier Inc., Box 1602, York, Pa., USA 17405. Tel. 717-767-6717. This company no longer manufactures the COJA Mill (Refer to RMD Inc.).

9. Kennedy Van Saun Corporation, Danville, Pa., USA. Tel. 717-275-3050. Ken Brame, telephone communication November 20, 1987.

APPENDIX I

MICRONIZED COAL TEST PROGRAMME [7]

A programme to characterize the chemical and physical properties and determine the combustion and deposition characteristics of micronized coal was planned by Stone & Webster Engineering Corporation (SWEC) and implemented in co-operation with Babcock & Wilcox Company (B&W). The testing was performed by the B&W Research Centre in Alliance, Ohio.

Test Objectives

The overall objectives of the programme are to investigate the technical and economic feasibility of converting oil and gas fired boilers to burn micronized coal. To establish technical feasibility, the programme will determine (1) the types of coal suitable; (2) how fine the coal must be pulverized (or, restated, how coarse a grind can be tolerated so that, with soot blowing, there is manageable and acceptable ash deposition; and (3) the extent of conversion modifications required. To establish economic feasibility, it will determine (1) the cost of micronized coal fuels (including pulverizing cost); (2) the cost of conversion modifications; and (3) the extent of boiler derating required (if any).

The programme was structured to have two small scale phases (which have been completed), to be followed by scaled-up testing in an industrial and/or utility boiler.

The specific objectives of the small scale testing phases were:

- Determine if the size of ash particles from burning micronized coal are smaller than those from conventional pulverized coal. This would confirm that the ash particles from micronized coal do not agglomerate appreciably in the combustion zone.
- Define the deposition characteristics of micronized coal ash.
- Determine if any differences in chemical composition exist between micronized coal ash and conventional pulverized coal ash.
- Investigate the effects of coal fineness on combustion and deposition.
- Determine the extent of particulate and gaseous emissions produced during the combustion of micronized coal.

To accomplish these objectives, three basic areas of work were required to compare characteristics of the micronized coal to those of conventional pulverized coal. These three areas were: (1) fuels characterization, (2) laboratory ashing furnace tests

and, (3) small scale combustion furnace tests. They are discussed below.

Fuels Characterization

Three types of coal (one each from West Virginia, Ohio and Indiana) were selected for evaluation of suitability as a micronized fuel for oil and gas burning boilers. Tables 1 and 2 present a comparison of the properties of these three coals. The West Virginia coal is a low ash content, high ash fusion temperature coal and should be the most likely of the three to have a low slagging potential. The Ohio and Indiana coals would be expected to have moderate and higher slagging potentials, respectively, because of their higher ash content and lower ash fusion temperatures.

These three coals were fully characterized by laboratory determinations of proximate and ultimate analyses, moisture, calorific value, sulphur forms, ash fusibility, grindability and elemental ash constituents. Additionally, burning profiles and volatile release profiles were generated for both the pulverized and micronized coals.

The burning profiles of the micronized and pulverized test coals indicated that the micronized coal ignites at a lower temperature and completes combustion earlier. This indicates that the micronized coal will produce a shorter and more intense flame than the conventional pulverized coal. The volatile release profiles of the micronized and conventional pulverized coals were different. The amounts of volatiles released were approximately equal, but the volatiles of the micronized coal were released at a more even rate over the temperature range.

Phase I - Laboratory Ashing Furnace Tests

The Phase I testing was performed in the Laboratory Ashing Furnace (LAF) at the B&W Alliance Research Centre. This is a 200,000 Btu/hr. test furnace designed to produce fly ash with properties similar to ash from a large utility boiler. The LAF, shown in Figure 1, consists of four major components: a pulverized fuel-feeding system; a refractory combustion chamber; a water-cooled pressurized boiler; and a system for collecting fly ash. The coal is burned within a silicon carbide combustion chamber, which is heated externally by a surrounding electric furnace. Primary and secondary air flows make up approximately 20 and 80% of the combustion air, respectively. The combustion gases and entrained fly ash pass into a vertical heat exchanger where they are cooled before the fly ash is collected in a cyclone separator and cloth filter bag.

Conventional pulverized and micronized grinds of the three test coals were burned in the LAF. Ceramic probes were inserted at the furnace exit to obtain indications of deposition on superheater tubes. The LAF was operated in such a way that a furnace exit gas temperature of about 2400°F was maintained, which is comparable to that of an oil designed unit. The ash from each

coal burned was collected from the LAF and analyzed for particle size, carbon content and elemental ash constituents.

Some very encouraging results were obtained from the test and analysis of fly ash produced in the LAF. They are summarized in Figures 2, 3 and 4.

Figure 2 compares the particle size distribution of fly ash from conventionally pulverized and micronized Indiana coal. The curves illustrate the proportion of ash particles smaller than the indicated sizes. The size of ash particles from micronized coal is seen to be much smaller than that from conventional pulverized coal.

This is confirmed by the 1500X magnification electron micrographs in Figure 3, which compare the size of ash particles from micronized and pulverized Indiana coal. These micrographs also show that ash particles from micronized coal did not agglomerate appreciably when this coal was burned in the LAF.

Figure 4 compares deposits of fly ash on ceramic probes when burning coal ground to micronized and pulverized grinds. It demonstrates that micronized coal ash particles were small enough to travel with the flue gas around the tubes, while pulverized coal ash particles did not, but impacted and deposited on the tube.

The bulk of the accumulated data supports a preliminary conclusion that conversion to micronized coal, instead of pulverized coal, will require less boiler modification and/or less boiler derating. Therefore, scaled-up tests in the Basic Combustion Test Unit (BCTU) followed.

Phase II - Small Scale Combustion/Deposition Testing

The objective of Phase II testing was to investigate the effects of coal fineness on combustion and deposition. It was conducted in B&W's 4 million Btu/hr. BCTU. This cylindrical furnace, 4.5 ft. in diameter and 8 ft. long is of water-cooled, double wall construction with a refractory brick lining over the internal area of the furnace. The unit is equipped with view ports permitting visual and photographic observation and allowing probing for gas temperature and ash collection.

In order to determine deposition characteristics of micronized coal fly ash, several modifications were made to the BCTU. The furnace section leading to the original convective tube banks was bricked shut. A test section was added to the existing BCTU furnace through which the flue gas was diverted. (See Figures 5 and 6.) This test section was designed to simulate a superheater section of boilers designed for oil and gas firing. Tubes were 2 in. OD on 3 in. centres. Gas velocities between the tubes were approximately 100 ft./s at nominal load. The first two banks of tubes were air-cooled and surface metal temperatures could be varied up to 1000°F. An air sootblower was installed for tube cleaning.

Phase II testing was performed using the same West Virginia Sewell No. 1 coal that was tested in the Phase I LAF testing. It had been intended that the coal be ground to 3° of fineness: (1) conventional pulverized grind (70% minus 200 mesh); (2) micronized, with a top size of 44 microns; and (3) finer micronized, with a top size of 15 microns. The micronizing was performed off-site, producing the mass fraction distributions of the micronized and finer micronized coals shown in Figure 7. It appears as if there is very little difference between these two samples; however, by calculating the number distributions from the mass fraction distributions and by plotting them on a histogram, definite differences in the samples appear, as shown in Figure 8.

The mass mean diameters were 9.4 and 8.3 microns for the micronized and finer micronized coal samples, respectively. The Sauter mean diameters* were 6.7 and 4.8 microns for the coarser and finer micronized coal samples, respectively.

The Phase II testing consisted of a 64 hour, around-the-clock deposition test preceded by a series of parametric combustion tests using micronized coal. In addition, some limited testing was performed using finer micronized coal. For comparison, some testing was performed using conventional pulverized coal.

The Phase II initial testing was performed using pulverized coal. Five parametric tests were planned for this grind, but before these could be completed, the deposition test section plugged with ash as shown in Figure 9. This occurred within seven hours after starting up on pulverized coal. Tube temperatures (surface metal temperature) during this period ranged from 400 to 600°F.

The micronized coal was then tested in the BCTU for 64 hours continuously. The tubes were blown with compressed air every hour and photographs were taken before and after sootblowing. Tube metal temperatures averaged around 900°-1000°F for these tests. The hourly sootblowing provided controllable deposition, as shown in Figures 10 and 11. Occasionally, the coal would hang up in the feed hopper, suddenly free itself and then start feeding again. When this happened, the coal feed rate would increase briefly and level out shortly. This, in turn, would increase the tube surface temperature about 100 to 200°F. A few times, the tube metal temperatures exceeded 1200°F due either to a coal surge or loss of a compressor supplying cooling air to the tubes. These high metal temperatures increased the deposition rates drastically. However, after the temperatures leveled out, the air sootblowing again cleaned the tubes quite well. The base deposit did not appear to grow over the extended test (i.e. the

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* The Sauter mean diameter, also known as the volume to surface mean diameter, is the mean diameter of a distribution that has the same surface to volume ratio as the overall distribution.

sootblowing seemed to clean the tubes to the same degree each time.)

The micronized coal was then tested under different excess air and load conditions in the BCTU. Figure 12 shows the relationship of NO_x emissions with load for the micronized coal. The increase in NO_x emissions with load is due to the higher furnace temperature and increased turbulence resulting in better fuel/air mixing.

As expected, the flames of the conventional pulverized and the flames of the coal ground to micronized and finer consists were visibly different (Figure 13). Because the particles of the micronized coals are smaller and the surface where combustion reactions can take place is larger than with pulverized coal, the particles burn in a shorter, brighter flame. The increased brightness is due to the more intense combustion (more heat released per unit volume) than is typically seen with conventional pulverized coal.

The flame from the conventional pulverized coal filled the entire furnace and was not as clear as the flame of the micronized coals.

The flame from the micronized coal was brighter than the flame from the pulverized coal but not as bright as the flame from the finer micronized coal. Occasionally, parts of the burner could be seen through the flame, but usually only a bright halo around the impeller could be seen through the orangish flame. This flame occupied about 80% of the furnace region.

The flame of finer micronized coal was very short. It extended from the burner about 2-4 ft. down the furnace (to about one-half of the furnace length). This flame was very bright orange to white and one could look into the flame from the back of the furnace and see the coal impeller and various parts of the burner; however, it was not as clear as the blue flame from natural gas.

Preliminary Conclusions

The LAF test results support the contention that ash deposition rates will be less for micronized coal than for pulverized coal. The results, though not completely conclusive, indicate that equipment modifications and/or plant derating will be significantly less in converting to coal if micronized coal is used instead of pulverized coal.

The shape of the flame when firing intermediate micronized coal in the BTCU was slightly different from a conventional pulverized coal flame; it did not occupy the entire furnace. The flame from the ultrafine micronized coal was significantly shorter.

The deposits formed on the tightly-spaced tube bank in the BCTU when firing micronized coal were removed by sootblowing with air.

During the 64 hour continuous test, tubes were blown every hour and base deposits (deposits on the tubes immediately after sootblowing) did not appear to increase with time. However, longer duration demonstration testing in full size boilers is required to confirm these test results and address the question of erosion. Plans for such scaled-up testing are currently being evaluated.

TABLE 1

MOISTURE, PROXIMATE, ULTIMATE AND SULFUR FORMS ANALYSES, CALORFIC VALUES FOR PARENT COALS

	Indiana Coal		Ohio Coal		West Virginia Coal	
	As Received	Dry	As Received	Dry	As Received	Dry
Total Moisture, %	13.0	---	5.2 ---	4.8	---	
Proximate Analysis, %						
Moisture	13.0	---	5.2	---	4.8	---
Volatile Matter	37.7	43.4	38.1	40.2	28.6	30.1
Fixed Carbon	41.2	47.3	48.1	50.7	62.5	65.6
Ash	8.1	9.3	8.6	9.1	4.1	4.3
Ultimate Analysis, %						
Moisture	13.0	---	5.2	---	4.8	---
Carbon	62.0	71.2	70.2	74.0	79.5	83.5
Hydrogen	4.5	5.1	4.9	5.1	4.8	1.29
Nitrogen	1.03	1.18	1.55	1.64	1.23	1.29
Sulfur	3.24	3.73	2.16	2.28	0.75	0.79
Ash	8.1	9.3	8.6	9.1	4.1	4.3
Oxygen (Difference)	8.13	9.49	7.39	7.88	4.82	5.22
Total	100.00	100.00	100.00	100.00	100.00	100.00
Sulfur Forms, % as S						
Pyritic	0.76	0.87	0.74	0.78	0.01	0.01
Sulfate	0.50	0.57	0.17	0.18	0.02	0.02
Organic (Difference)	1.98	2.29	1.25	1.32	0.72	0.76
Total	3.24	3.73	2.16	2.28	0.75	0.79
Gross Calorific Value						
Btu/lb	11,100	12,760	12,540	13,230	14,000	14,710
Btu/lb Moisture and ash free	------	14,080	------	14,550	------	15,380

TABLE 2

ASH ANALYSES AND ASH-FUSION TEMPERATURES FOR ASH FROM PARENT COALS

	Indiana Coal		Ohio Coal		West Virginia Coal	
Ash Analysis (Spectrographic),%						
SiO_2	43.53		50.58		44.87	
Al_2O_3	20.34		24.62		27.85	
Fe_2O_3	22.02		17.16		13.06	
TiO_2	0.96		1.10		1.17	
CaO	4.06		1.13		3.39	
MgO	0.77		0.62		1.16	
Na_2O**	0.46		0.39		1.02	
K_2O**	2.41		1.99		2.11	
SO_3	4.40		1.11		4.08	
P_2O_5	0.61		0.39		0.54	
Ash Fusion Temperatures, °F						
Atmosphere	Red.	Oxid.	Red.	Oxid.	Red.	Oxid.
Initial Deformation Temperature (IT)	2,000	2,380	2,220	2,560	2,310	2,610
Softening Temperature (ST)B	2,090	2,490	2,440	2,640	2,500	2,670
Hemispherical Temperature (HT)	2,130	2,520	2,470	2,650	2,520	2,690
Fluid Temperature (FT, 1/16")**	2,260	2,560	2,570	2,670	2,570	2,720
Fluid Temperature (FT, Flat)	2,570	2,650	2,750+	2,750+	2,750+	2,750+

NOTES:

*By flame photometer
**Temperature at which the fused mass was spread out in nearly flat layer with minimum height of 1/16 inch.

SCHEMATIC DIAGRAM OF LABORATORY ASHING FURNACE

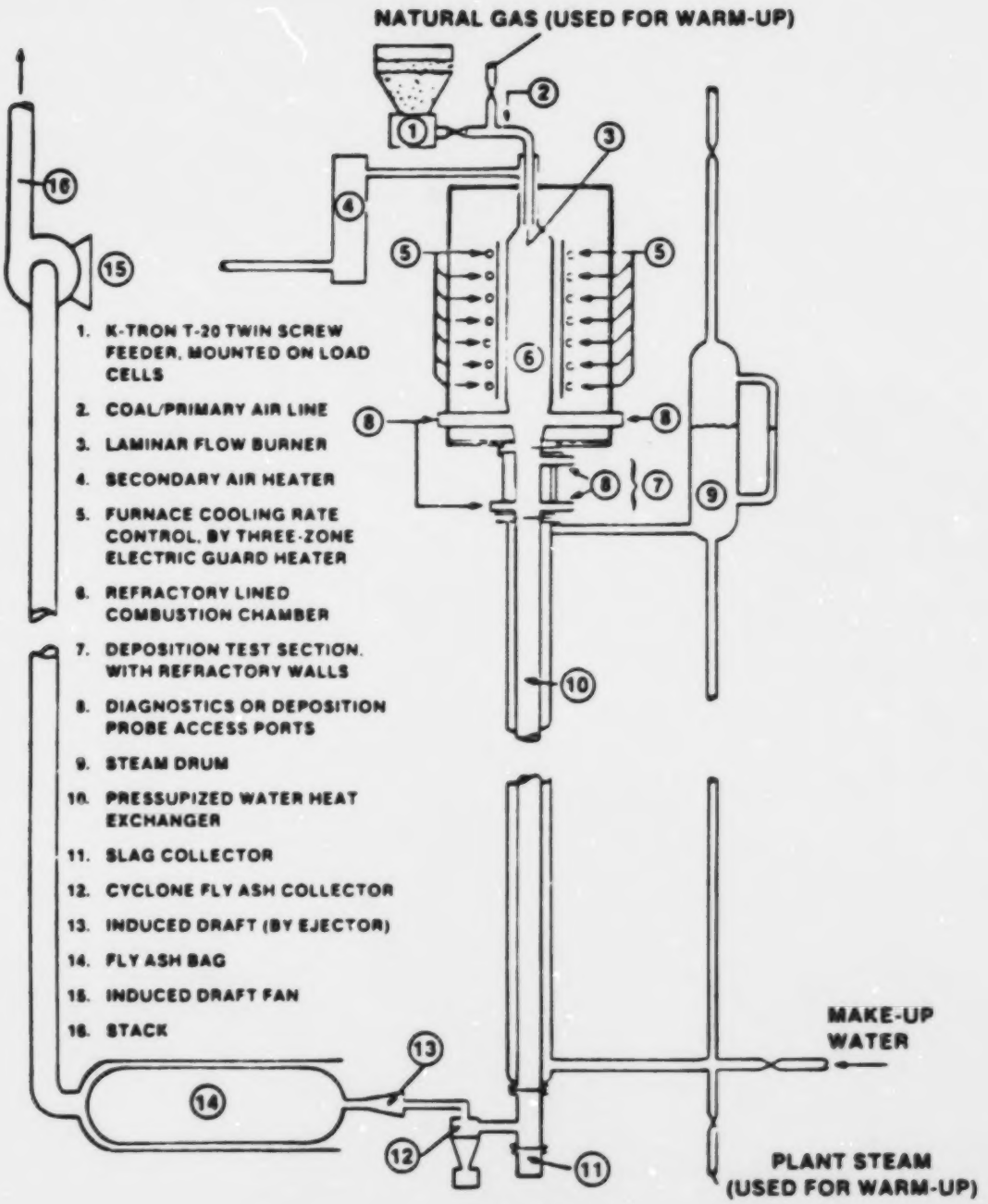

NATURAL GAS (USED FOR WARM-UP)
1. K-TRON T-20 TWIN SCREW FEEDER, MOUNTED ON LOAD CELLS
2. COAL/PRIMARY AIR LINE
3. LAMINAR FLOW BURNER
4. SECONDARY AIR HEATER
5. FURNACE COOLING RATE CONTROL, BY THREE-ZONE ELECTRIC GUARD HEATER
6. REFRACTORY LINED COMBUSTION CHAMBER
7. DEPOSITION TEST SECTION, WITH REFRACTORY WALLS
8. DIAGNOSTICS OR DEPOSITION PROBE ACCESS PORTS
9. STEAM DRUM
10. PRESSUPIZED WATER HEAT EXCHANGER
11. SLAG COLLECTOR
12. CYCLONE FLY ASH COLLECTOR
13. INDUCED DRAFT (BY EJECTOR)
14. FLY ASH BAG
15. INDUCED DRAFT FAN
16. STACK
MAKE-UP WATER
PLANT STEAM (USED FOR WARM-UP)

FIGURE 1

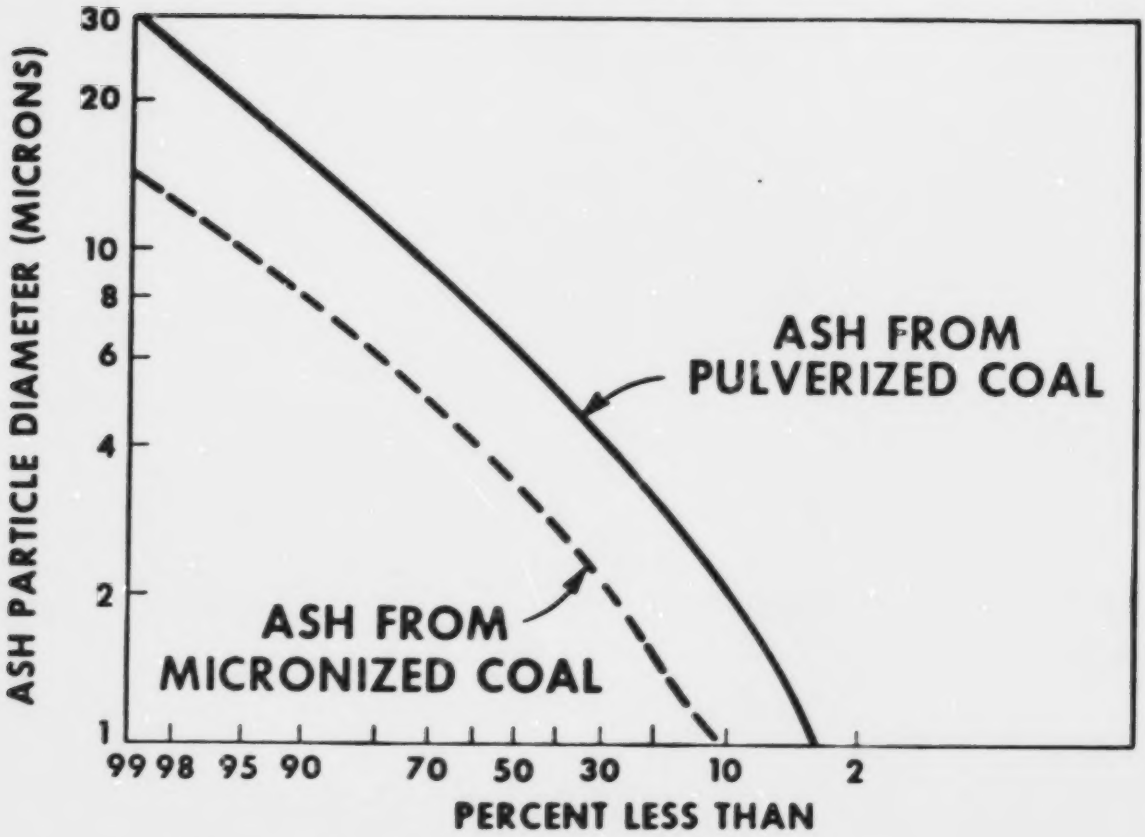
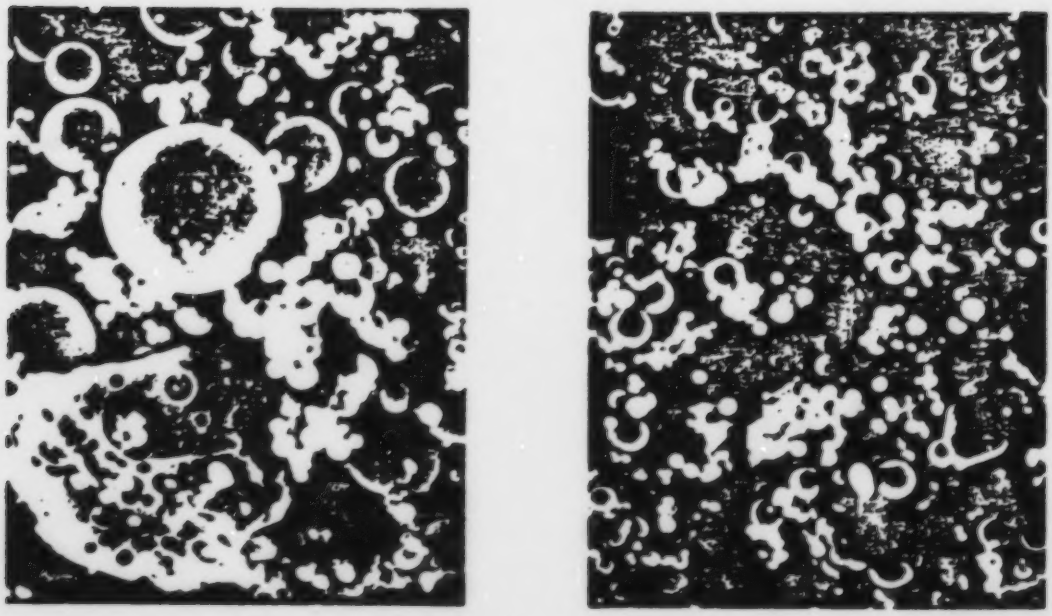


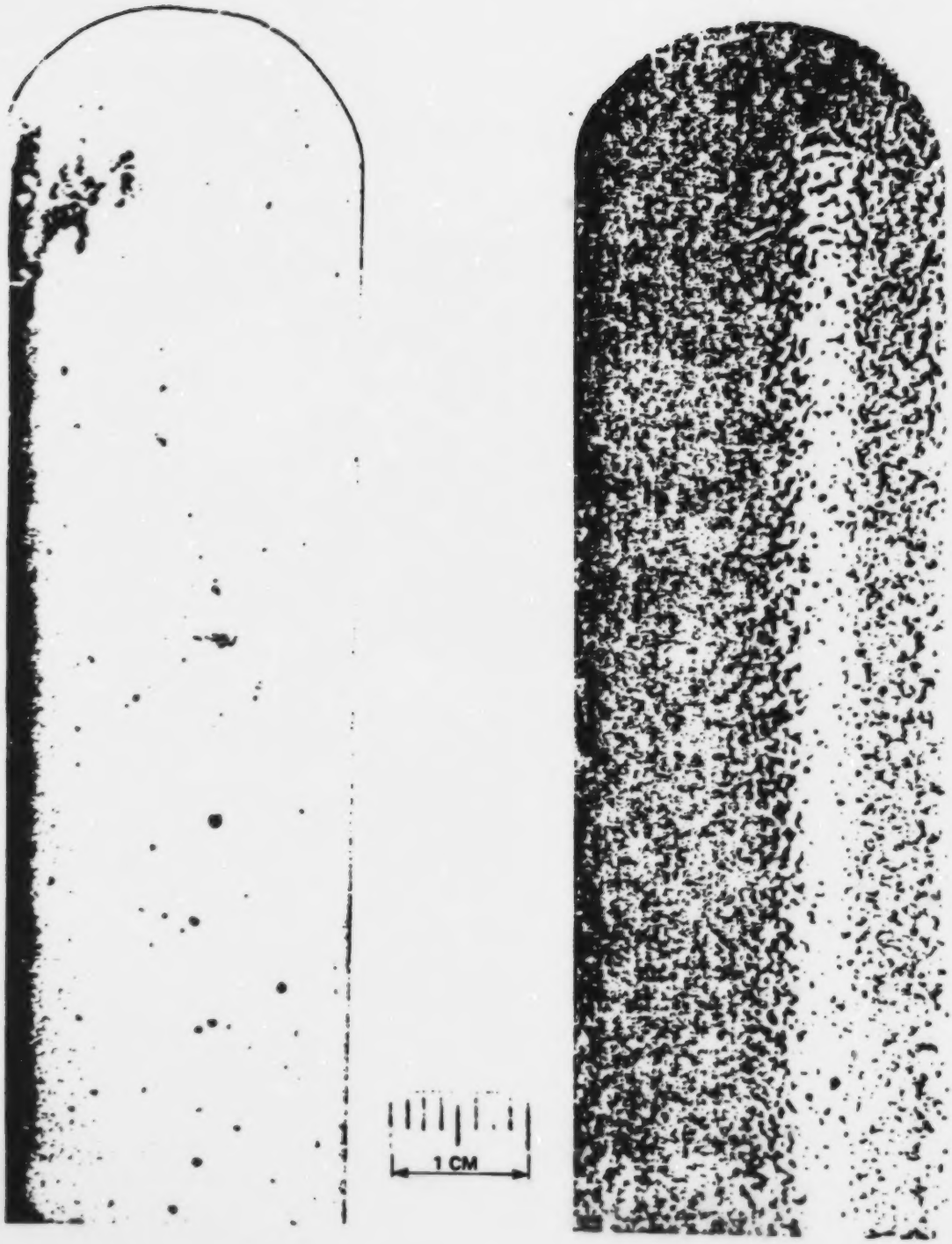
FIGURE 2 ASH FROM LAB ASHING FURNANCE INDIANA COAL



1500X
PULVERIZED COAL ASH

1500X
MICRONIZED COAL ASH

FIGURE 3 COMPARISON OF ASH PARTICLES FROM PULVERIZED AND MICRONIZED COAL



MICRONIZED COAL TEST

PULVERIZED COAL TEST

NOTE THE BLACK MATERIAL IS THE DEPOSIT

FIGURE 4 COMPARISON OF DEPOSITS FROM MICRONIZED AND PULVERIZED COALS

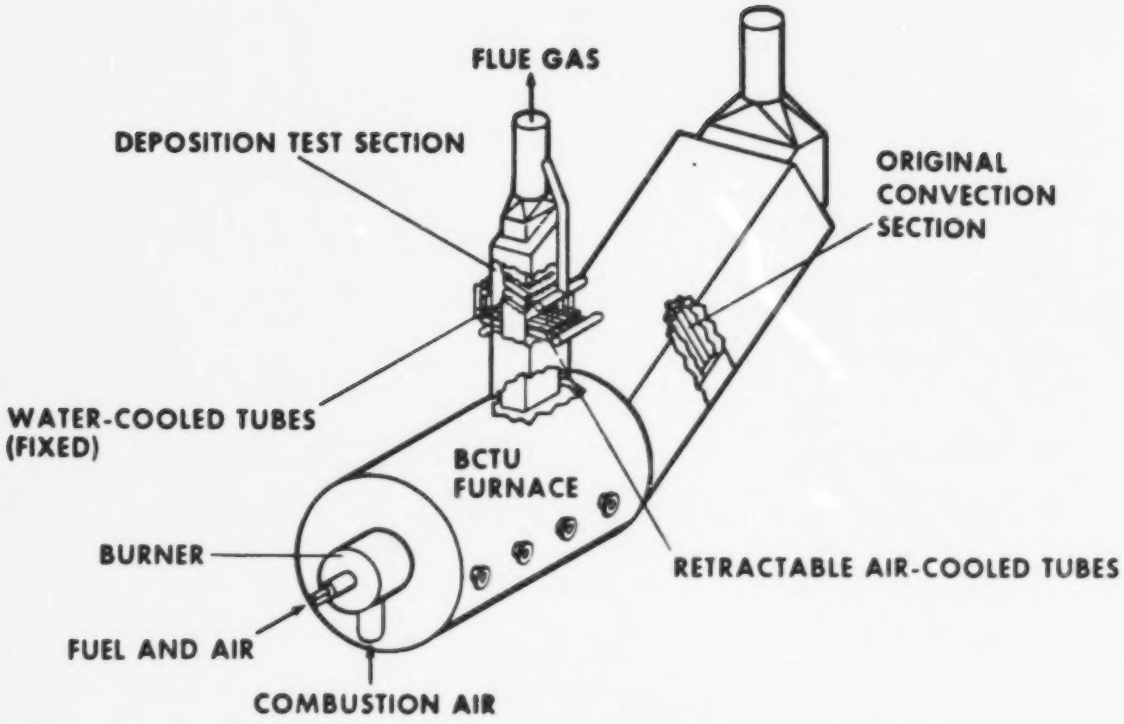


FIGURE 5 MODIFIED BASIC COMBUSTION TEST UNIT

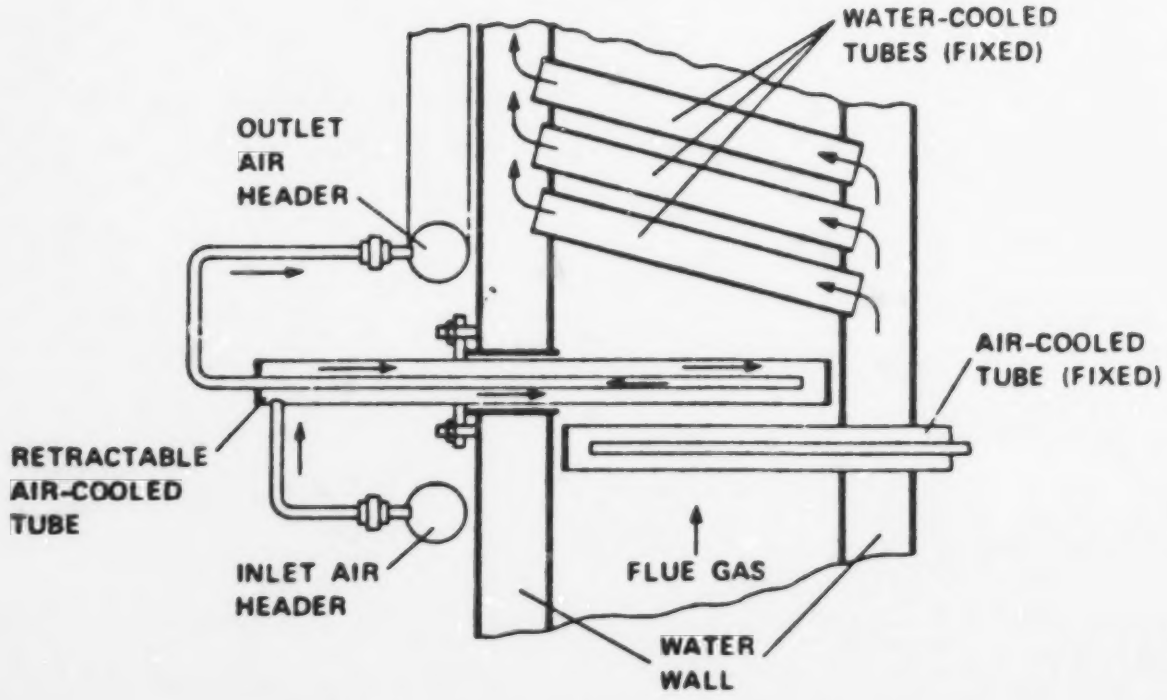


FIGURE 6 DETAIL OF DEPOSITION TEST SECTION

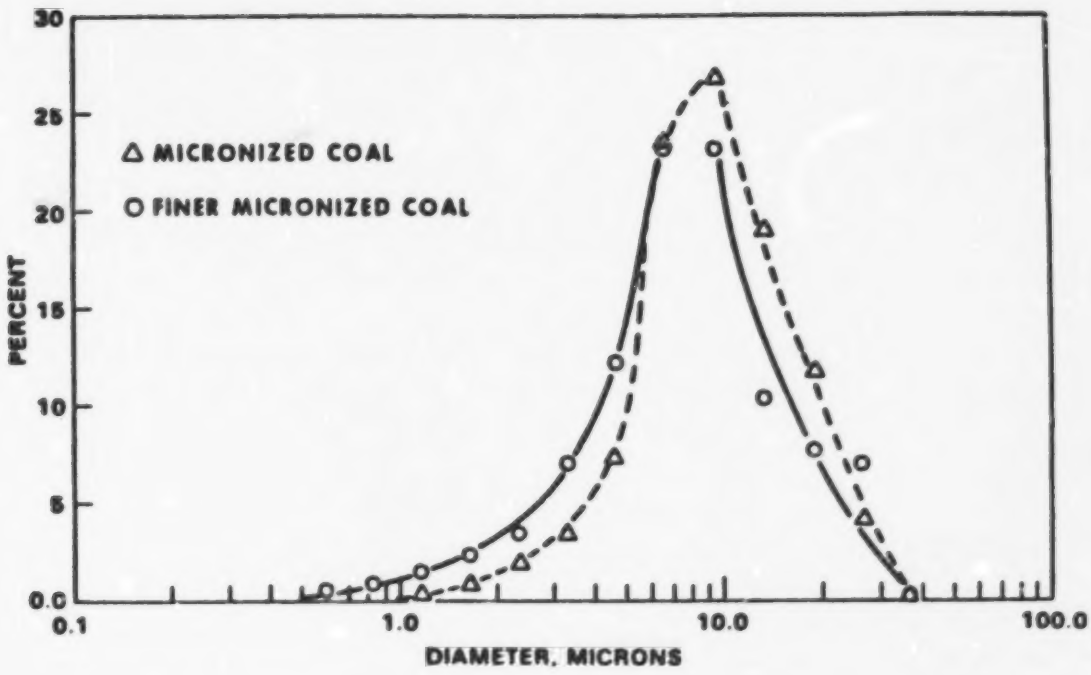


FIGURE 7 MASS FRACTION DISTRIBUTION OF COAL SAMPLES

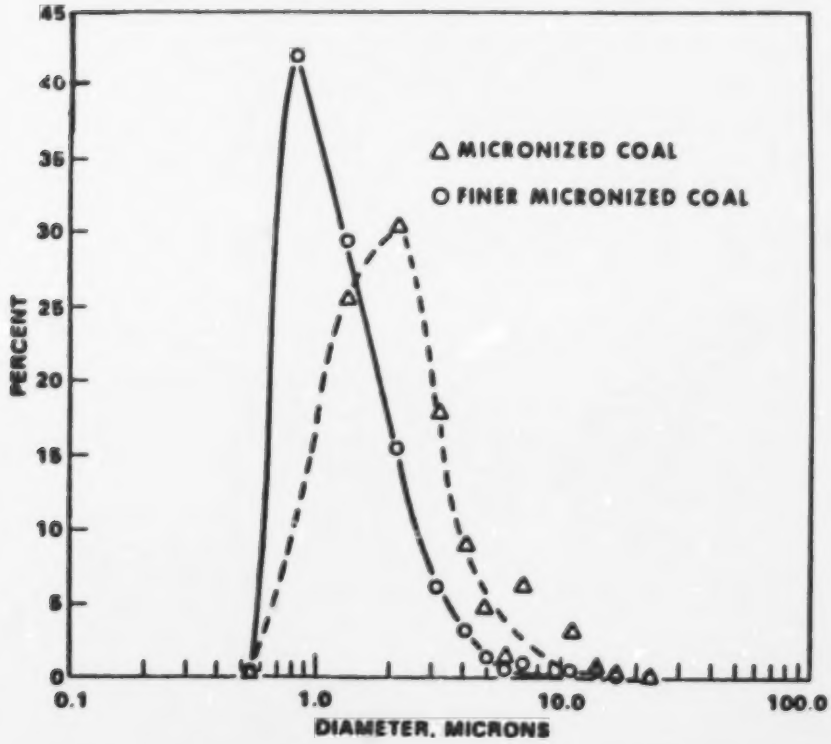


FIGURE 8 NUMBER DISTRIBUTION OF COAL SAMPLES

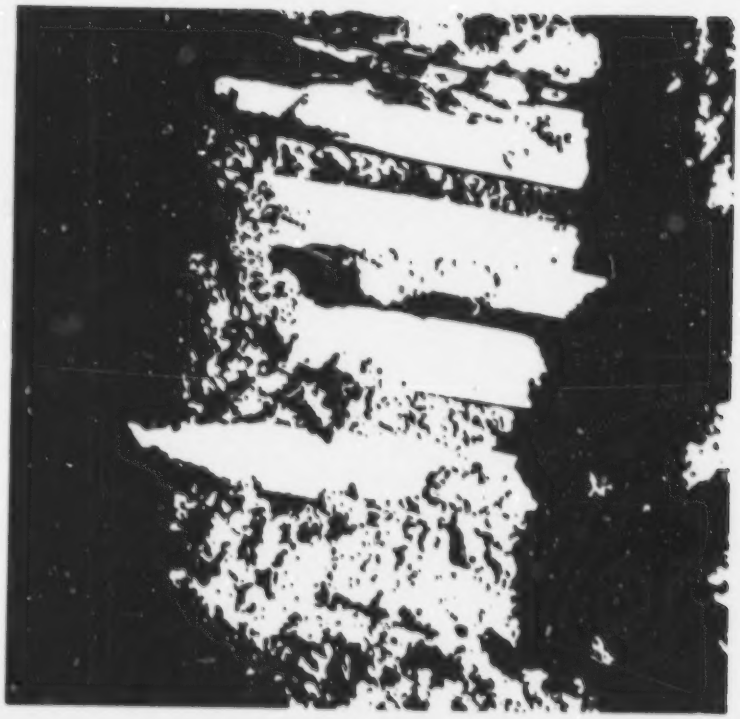


FIGURE 9 PLUGGED TUBE BANK DURING PULVERIZED COAL PARAMETRIC TESTING (WITHOUT SOOTBLOWING)

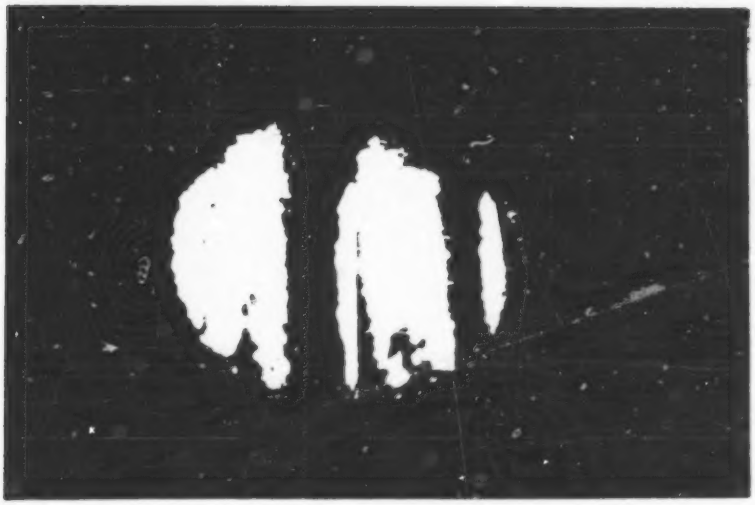


FIGURE 10 AIR-COOLED TUBES PRIOR TO SOOTBLOWING

FIGURE 11 AIR-COOLED TUBES IMMEDIATELY AFTER SOOTBLOWING

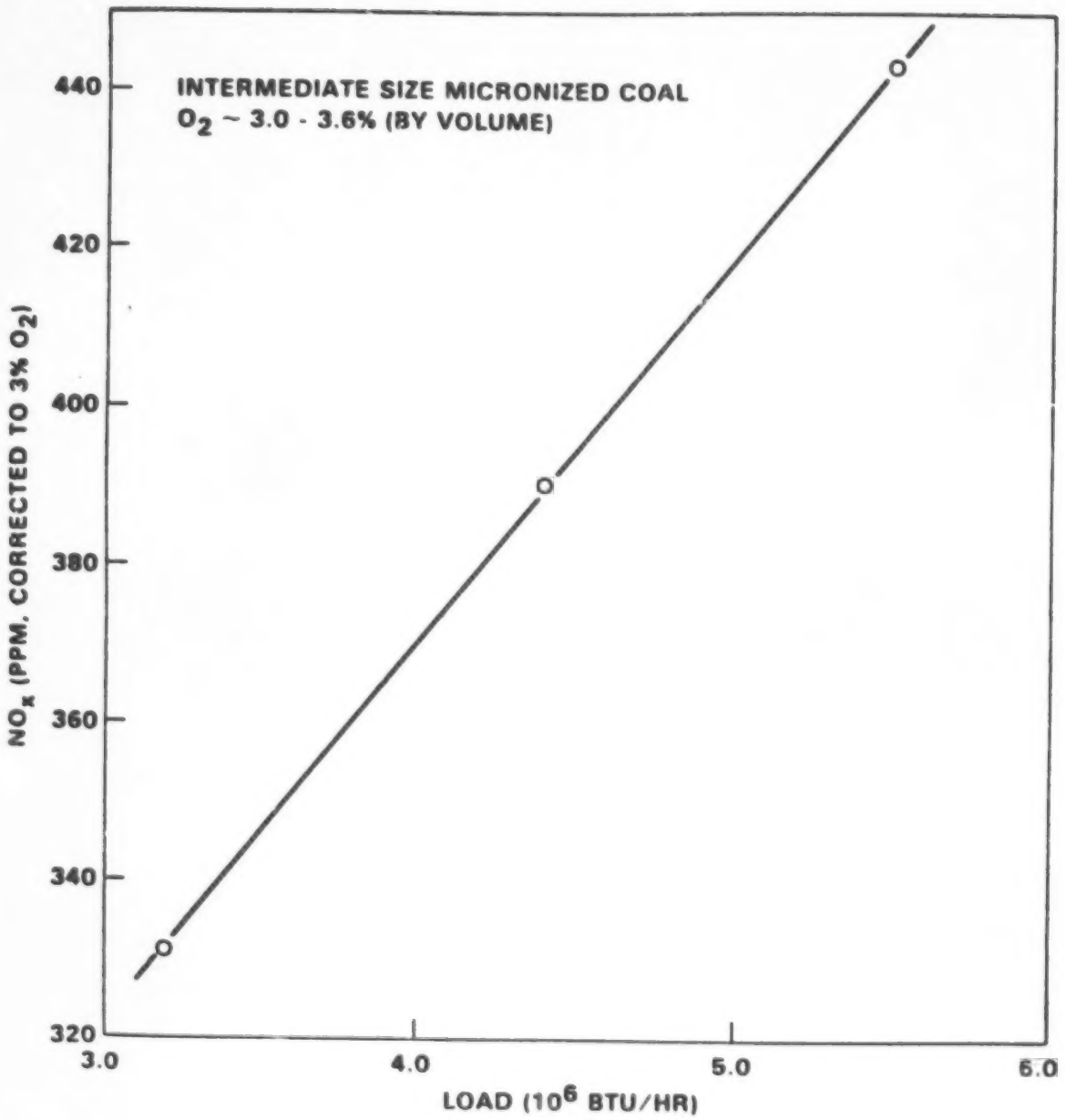
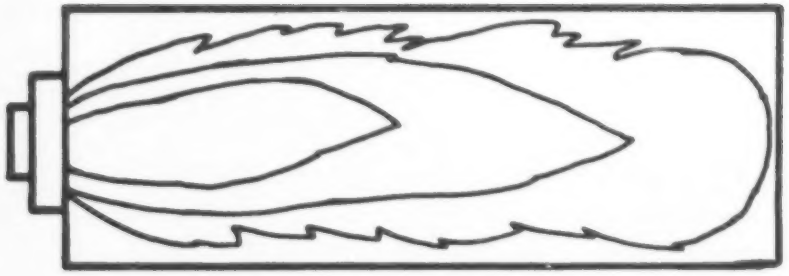


FIGURE 12 NOx-LOAD RELATIONSHIP

STONE & WEBSTER

COMPARISON OF FLAME LENGTH FOR PULVERIZED AND MICRONIZED COAL



PULVERIZED COAL FLAME

MICRONIZED COAL FLAME

FINER MICRONIZED COAL FLAME

STONE & WEBSTER

FIGURE 13